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Icarus 185 (2006) 171–196
ICARUS
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Paucity of candidate coastal constructional landforms along proposed shorelines on Mars: Implications for a northern lowlands-filling ocean

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Received 8 June 2005; revised 1 June 2006

Available online 14 August 2006

Abstract

The case for an ocean having once occupied the northern lowlands of Mars has largely been based indirectly on the debouching of the outflow channels into the lowlands, and directly on erosional features along the margins of the lowlands interpreted to be the result of wave action. Two global shorelines were previously mapped from albedo variation, embayment relationships, and scarps interpreted as coastal cliffs. However, not since the early, Viking-based studies, has there been a focused assessment of the presence or absence of coastal constructional landforms such as barrier ridges and spits, located on or near the mapped "shorelines." Such constructional landforms are typically found in association with coastal erosional features on Earth, and therefore warrant a detailed search for their presence on Mars. All presently available THEMIS VIS and MOC NA images located on or near either of the two "shorelines," within the Chryse Planitia/Arabia Terra region (10° to 44° N; 300° to 0° E) and the Isidis Planitia region (0° to 30° N; 70° to 105° E), were examined in search of any features that could reasonably be considered candidate coastal ridges. Additionally, raw MOLA profiles were used in conjunction with a technique developed from Differential Global Positioning System profiles across terrestrial paleo-shorelines, to search for coastal ridges throughout these same regions. Out of 447 THEMIS VIS and 735 MOC NA images examined, only four candidates are observed that are plausibly interpreted as coastal ridges; no candidate coastal ridges are observed in the MOLA profiles. This overwhelming paucity of candidate features suggests one of five possible scenarios in terms of the existence of standing bodies of water within the martian lowlands: (1) No ocean existed up to the level of either of the previously mapped "shorelines"; (2) An ocean existed, however wave action, the primary agent responsible for construction of coastal landforms, was minimal to non-existent; (3) An ocean existed, but sediment input was not significant enough to form coastal deposits; (4) An ocean existed, but readily froze, and over time sublimated; and lastly (5) An ocean existed and coastal landforms were constructed, but in the intervening time since their formation they have nearly all been eroded away.

Keywords: Mars; Mars, surface; Mars, climate

1. Introduction

1.1. Background and previous studies

The northern lowlands, occupying approximately one third of the surface area of Mars, and measuring approximately 2–3 km below the planetary datum (Smith et al., 1998), has often been proposed as a site of former standing bodies of water (Parker et al., 1989, 1993; Baker et al., 1991; Head et al., 1999). Initially this general hypothesis was implicit within the literature, as the tens-to-hundreds of kilometers wide, and thousands of kilometers long outflow channels that debouch into the lowlands came to be attributed to the catastrophic breakout and discharge of enormous volumes of water onto the surface (Baker and Milton, 1974; Baker, 1978, 1979, 1982; Theilig and Greeley, 1979). Naturally such large-scale floods, even if they occurred under climatic conditions similar to the present, and consequently experienced considerable volumetric loss due to sublimation (e.g., Kreslavsky and Head, 2002a), would still have resulted in the accumulation of large lakes, or perhaps even seas and oceans within the northern plains.

Lucchitta et al. (1986) were the first to explicitly call upon the presence of standing water, albeit in a partially frozen

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doi:10.1016/j.icarus.2006.06.007

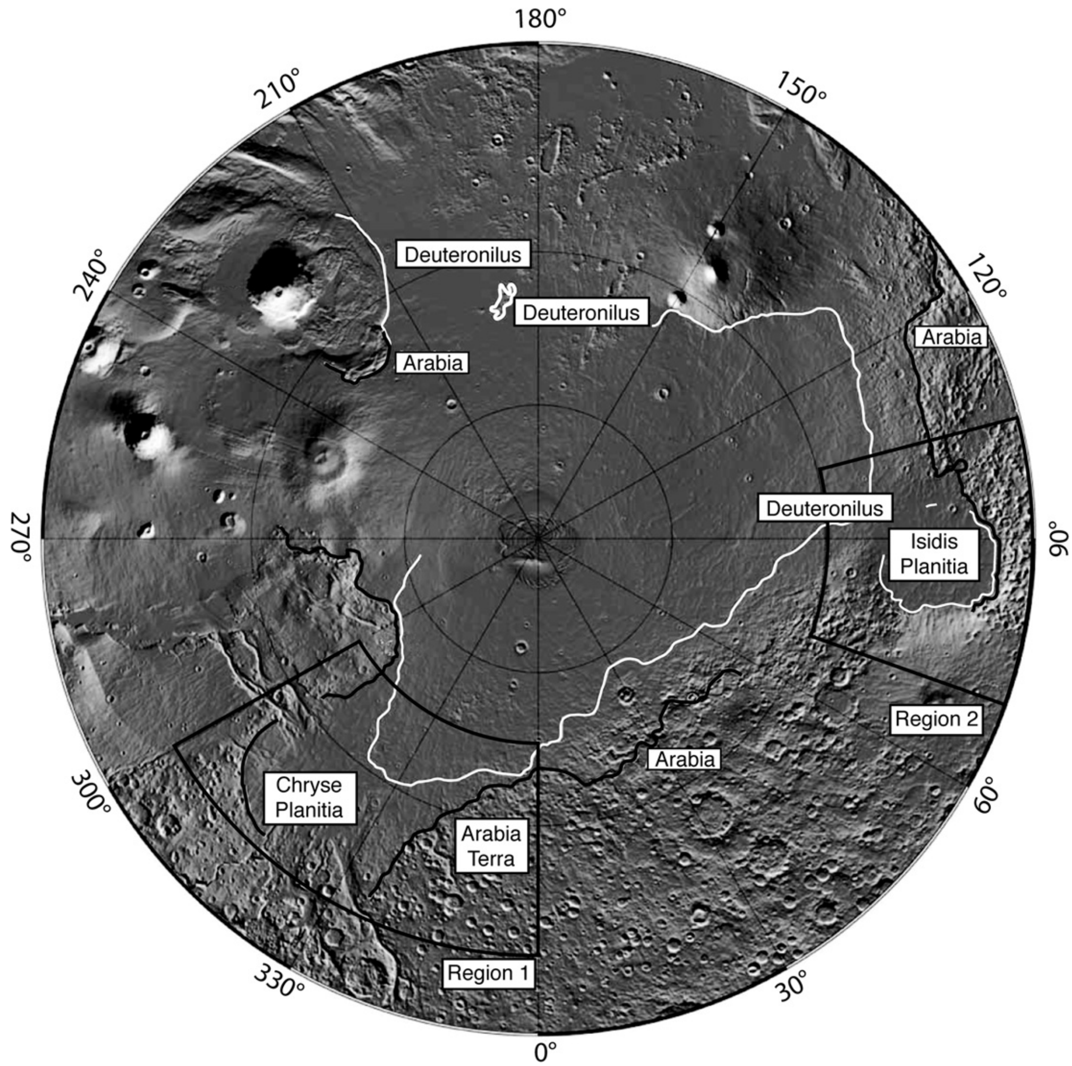

Fig. 1. MOLA polar stereographic projection shaded relief view of the martian northern hemisphere. Black line indicates the Arabia "shoreline" and white line the Deuteronilus "shoreline" of Clifford and Parker (2001). Chryse Planitia and Arabia Terra encompass study region 1 and Isidis Planitia study region 2. Figure adapted from Carr and Head (2003).

state, to explain landforms observed in the lowlands, specifically polygonal terrain present down slope of the outflow channels. Shortly thereafter Parker et al. (1989), based on studies of the gradational and fretted terrain segments of the dichotomy boundary separating the southern highlands and northern lowlands, and particularly a detailed analysis of the west Deuteronilus Mensae region, identified two global geologic/geomorphic contacts, which they interpreted as shorelines from a former lowlands-filling ocean (Fig. 1). Using Viking Orbiter images, these contacts were identified primarily from albedo variations, onlap and embayment relationships interpreted as due to sediment deposited in standing water, and scarps along massifs and fretted canyon walls, interpreted as wave-cut cliffs. Further support for the ocean hypothesis was the near total absence of valleys and channels north of these contacts, perhaps suggesting termination at standing water. Locally, within a Deuteronilus fretted canyon, "ridges and swales" were observed and interpreted as coastal features. The southern, and thus higher standing of the two contacts was referred to as Contact 1 (renamed the Arabia shoreline (Parker, 1998; Clifford and Parker, 2001)), and the northern contact as Contact 2 (now the Deuteronilus shoreline).

Parker et al. (1993) expanded their study to the Cydonia Mensae region (northern Arabia Terra/southern Acidalia Planitia), and the Isidis Planitia region. Cited as additional evidence from these areas in support of the ocean hypothesis were massifs with surrounding flat aprons in Cydonia interpreted as wave-cut islands with shore platforms (see also Parker and Currey, 2001); curvilinear ridges in Cydonia and more prominently within the Isidis basin interpreted as barrier ridges and spits; and small domes in Cydonia and Isidis interpreted as pingos, resulting from wet sediments that experienced later freezing. While Parker et al. (1989, 1993) envisioned a lowlands-filling ocean, Scott et al. (1991, 1995) independently mapped what they interpreted as shorelines for several, largely disconnected lakes and seas that once occupied enclosed basins within the northern hemisphere of Mars.

With the arrival of the Mars Global Surveyor (MGS), new instruments and measurements became available to test the ocean hypothesis. Using the topographic data provided by the Mars

Orbiter Laser Altimeter (MOLA) (Zuber et al., 1992), Head et al. (1998, 1999) examined the elevation range along the two Parker et al. (1989, 1993) contacts and concluded that Contact 2 (Deuteronilus), although not Contact 1 (Arabia), generally approximates an equipotential line, consistent with it representing a shoreline that has experienced minimal post-formation isostatic adjustment at the global scale (Leverington and Ghent, 2004). However, using the 2–20 m/pixel resolution images obtained by the Mars Orbiter Camera (MOC) (Malin et al., 1992) (a considerable increase in resolution as compared with the Viking images from which the contacts were originally mapped), Malin and Edgett (1999) examined 14 MOC narrow angle images along the proposed "shorelines" and concluded that none of the images showed features of "obvious or unambiguous littoral origin." Malin and Edgett (2001) examined additional MOC images along the "shorelines" and again concluded that none of the observed features were clearly related to the former presence of a northern ocean.

In addition to refining the trace of their proposed global "shorelines," Parker (1998) and Clifford and Parker (2001) used the new MGS data to identify several regional contacts, not continuous at the global scale. Further, Clifford and Parker (2001) took issue with the conclusions of Malin and Edgett (1999), asserting that one of the MOC images Malin and Edgett (1999) interpret as lacking evidence in support of the ocean hypothesis in fact displays geomorphic relationships consistent with sediments deposited in standing water. Clearly further examination of images along the "shorelines" is required before any concrete conclusions can be drawn about the existence of a lowlands ocean.

More recently, in their assessment of the ocean hypothesis, Carr and Head (2003) suggested that the shorelines mapped by Parker et al. (1989, 1993) and Clifford and Parker (2001) are more readily interpreted as mass-wasting and volcanic flow emplacement features. Rather than dismissing the ocean hypothesis, Carr and Head (2003) instead argued that the best evidence for a paleo-ocean is found interior to the lowlands (e.g., Lucchitta et al., 1986; McGill, 1986), not along its margins. In particular, Carr and Head (2003) suggested that the Vastitas Borealis formation (VBF), a Hesperian-aged deposit that covers much of the northern plains, and whose southern boundary corresponds well in places to the Deuteronilus "shoreline," represents a sublimation residue from the ponded effluents of the outflow channels. Evidence presented in support of this scenario is the comparable age and total volume of the VBF with that of the outflow channels, the presence of the VBF at the ends of the channels, and features within the VBF interpreted as due to basal melting of a large-scale ice body.

In the first detailed regional study utilizing post-Viking data, and the most recent addition to the ocean discussion, Webb (2004) examined the northern Arabia Terra/Cydonia Mensae region using MOLA data as well as Viking, MOC and Thermal Emission Imaging System (THEMIS) visible and infrared images (Christensen et al., 2004) in order to evaluate evidence for coastal erosion. Webb (2004) demonstrated that both the Arabia and Deuteronilus "shorelines" regionally follow equipotential lines to within a few tens of meters, considerably better than the more than half a kilometer standard deviation determined by Head et al. (1999) for Contact 2 (Deuteronilus) at the global scale. Webb (2004) suggested that locally the Deuteronilus "shoreline" is better approximated by two contours, one at −4000 m, and another at −4200 m, with the Arabia "shoreline" approximated by a −3707 m contour, indicating up to three distinct regional still stands. Additionally, Webb (2004) cited the presence of benches and scarps as evidence for the wave-cut nature of these contacts, perhaps calling into question Carr and Head's (2003) dismissal of coastal evidence for an ocean.

Questions about the timing, duration, re-occurrence, state, and extent of any large, standing body of water naturally follow the question of whether any such body existed. Did an ocean form during the Noachian as a natural consequence of the hydrological evolution of the planet (Clifford and Parker, 2001)? Did the effluents of the outflow channels yield an ocean during the Hesperian (Parker et al., 1989, 1993), and if so, does this require the various outflow channels to have formed much closer in time than suggested by crater counts of their floors? Did ocean formation occur at several periods throughout Mars' history, as a regular response to repeated warming events (Baker et al., 1991)? Was an ocean in the liquid state for long, or did it rapidly freeze (Lucchitta et al., 1986) and sublimate (Kreslavsky and Head, 2002a), suggesting a similar climate to that of today?

Clearly the past presence of standing bodies of water within the northern lowlands remains unresolved. As the existence of such lakes, seas or oceans has profound implications for the evolution of the martian surface, the transport of water and other volatiles across the planet, and the development and support of possible life, further studies utilizing recently acquired data from on-orbit spacecraft are warranted and necessary.

1.2. Current study

This contribution seeks to place some constraints on the conditions under which an ocean may have occurred, and the nature of that ocean. To date, geomorphic evidence presented for the existence of large, standing bodies of water within the northern lowlands has primarily been in the form of either marginal features interpreted as wave-cut *erosional* landforms, or interior features and terrain interpreted as ocean sedimentary deposits. As noted above, curvilinear ridges within Isidis and Cydonia were cited by Parker et al. (1993), but with the exception of a single MOC image discussed by Clifford and Parker (2001), absent from the recent debate is the presence, or lack thereof, of *coastal constructional* landforms, such as barrier ridges, progradational complexes, pocket barriers, spits, looped barriers, and tombolos, typically found in association with wave-cut benches and other coastal erosional landforms on Earth (King, 1972; Adams and Wesnousky, 1998).

Reported here are the results from a detailed examination of the Arabia and Deuteronilus "shorelines" within two regions along the northern lowlands margin, in search of any features that could reasonably be interpreted as coastal constructional landforms (Figs. 1 and 2). Throughout this study, the phrase

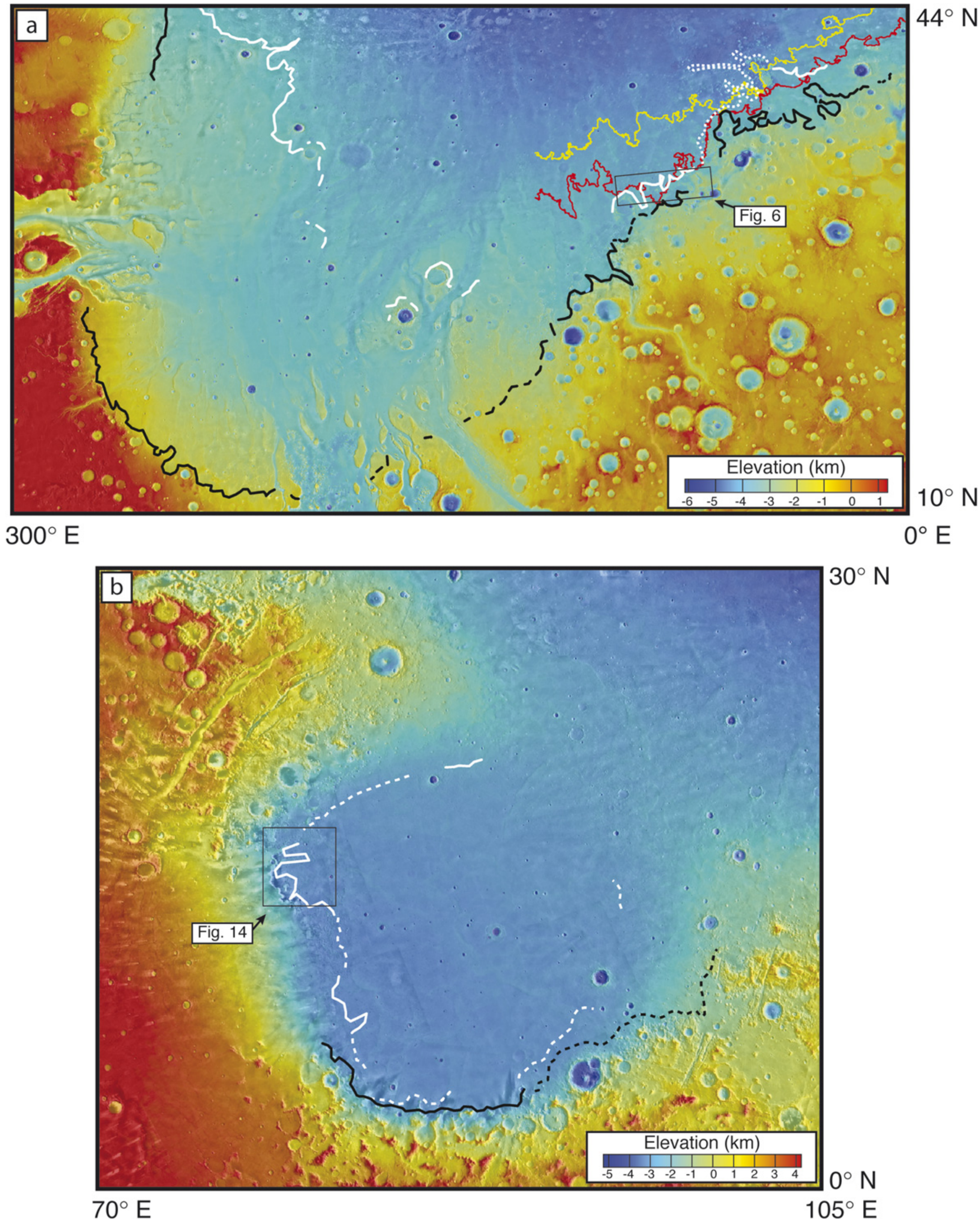

Fig. 2. (a) MOLA color-coded topography overlain on Viking MDIM 2.1 of the Chryse Planitia/Arabia Terra region. Black line indicates the Arabia "shoreline" and white line the Deuteronilus "shoreline" of Clifford and Parker (2001). Additionally, red line indicates the −4000 m contour and yellow line the −4200 m contour, proposed by Webb (2004) as possible regional shorelines. Black box corresponds to the Parker et al. (1993) study region in western Cydonia Mensae (see Fig. 6). (b) MOLA color-coded topography overlain on Viking MDIM 2.1 of the Isidis Planitia region. Black line indicates the Arabia "shoreline" and white line the Deuteronilus "shoreline." Black box corresponds to the Parker et al. (1993) study region in northwestern Isidis (see Fig. 14). These and all subsequent images of Mars are shown in simple-cylindrical projection.

"reasonable candidates" is used to refer to ridges for which the best possible interpretation seems to be a coastal landform. If an ocean once occupied the northern lowlands, depositing sediment and through wave action eroding cliffs recognizable in orbital images (Parker et al., 1989, 1993; Webb, 2004), it is reasonable to hypothesize that constructional features were formed as well, and should also be observable in orbital images. Mirroring the study regions of Parker et al. (1993) this examination focuses on the Arabia Terra/Acidalia Planitia region (Fig. 2a) and the Isidis Planitia region (Fig. 2b), although the Chryse Planitia region, adjacent to Arabia/Acidalia, is incorporated as well. Selecting these areas allows the present study to build on the previous Viking-based work of Parker et al. (1993), as well as the MGS/Odyssey-based analysis of Webb (2004). The selection of these regions also addresses a possible complication that may arise due to the presence of the recently discovered latitude-dependent mantle (Mustard et al., 2001; Kreslavsky and Head, 2002b; Head et al., 2003). Measuring up to tens of meters thick, this mantle, although discontinuous between 30° and 60° N, where much of Arabia is located, could possibly still obscure identification of landforms such as barrier ridges. The expansion of the first study area to include Chryse, and the study of Isidis, two regions that should be free from obstruction by the latitude-dependent mantle, should limit the degree to which any mid-latitude coastal constructional features may be obscured from observation if present.

2. Approach and methodology

2.1. Terrestrial coastal constructional landforms

A wide variety of constructional landforms occur along the coasts of standing bodies of water on Earth, and vary in scale, shape, orientation and composition due to multiple local factors including sediment availability, wave behavior and fetch, storm activity, offshore slope, etc. A comprehensive review is beyond the scope of this paper, but can be found in King (1972).

The variety of features of concern here include barrier ridges/islands (offshore ridges attached to the mainland at both ends), beach ridges (onshore ridges), spits (ridges attached at one end to islands or the mainland), and tombolos (ridges attached at both ends to islands or stretching between an island and the mainland), as well as barrier complexes (multiple, closely spaced ridges) and looped barriers (ridges attached at both ends to the same island) (King, 1972; Adams and Wesnousky, 1998).

Of particular importance is the variation in scale with which the above-described features occur, most notably barrier ridges. Off the eastern coast of the continental United States, barrier ridges extend from New England to South Carolina, generally located within a few kilometers of the coast (although occasionally several tens of kilometers offshore), and measure about 1–2 km across (Fig. 3a). These barriers occur as single ridges as opposed to multiple, closely spaced ridges such as occur in paleo-lakes in the western U.S. For example, several tens of stacked ridges measuring tens of meters across can be found within many of the graben of the Basin and Range region, once the sites of lakes during the last glacial maximum (Fig. 3b) (Mifflin and Wheat, 1979). These paleo-lakes were generally restricted to individual graben, measuring up to tens of kilometers long, although in some cases several graben-filled lakes merged to form larger, interconnected bodies, most notably with Lake Lahontan, which occupied much of northwestern Nevada (Morrison, 1964). This variation in scale and number of barriers, predominantly attributable to the stability of lake/sea level, as well as the wave fetch within the body of water, must be taken into account during any search for martian features of comparable origin.

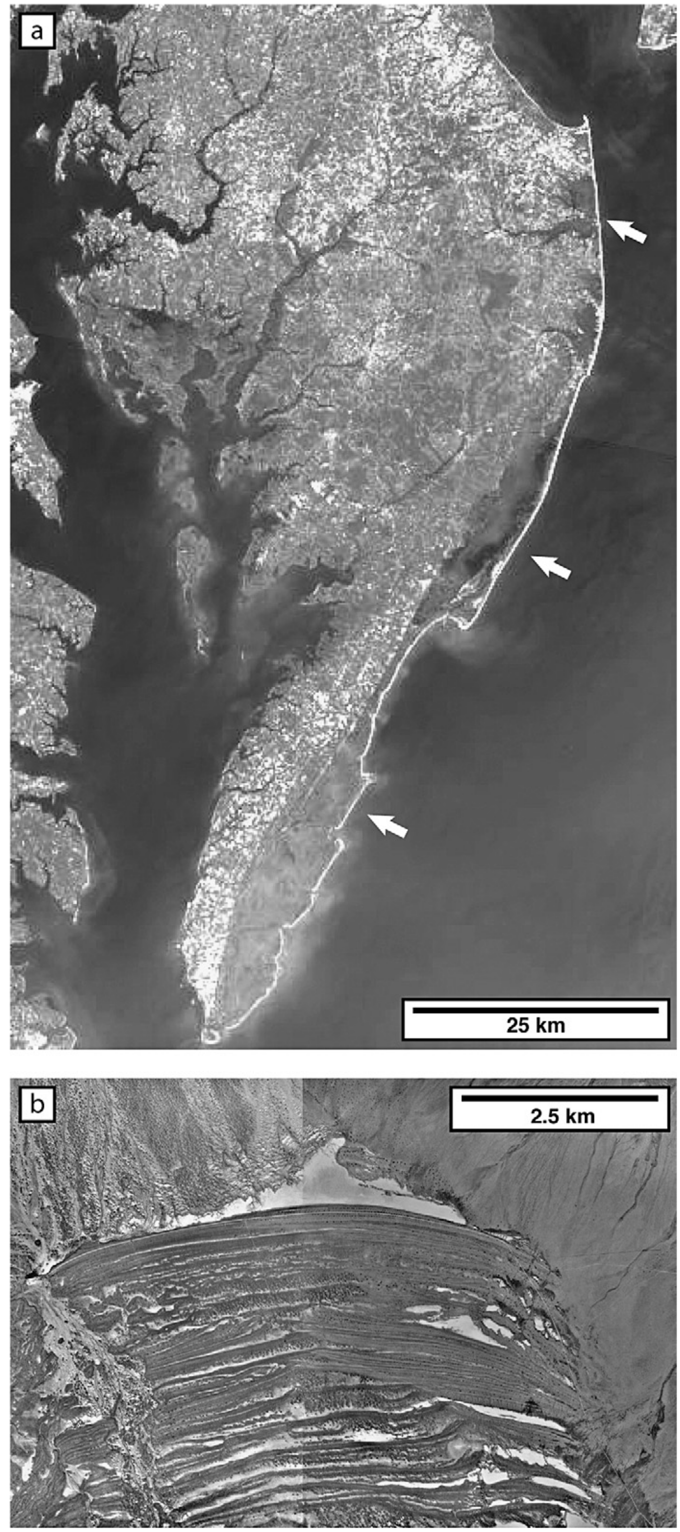

Fig. 3. Examples of terrestrial coastal constructional landforms. (a) Mosaic of Landsat 7 ETM+ images, Path 14, Rows 33 and 34, of the east coast of the U.S. in the Delaware region. White arrows indicate barrier ridge. (b) Portion of Digital Orthophoto (DOQ) data of north end of Spring Valley, NV (39.6° N, 114.6° W). Shorelines are seen as gray arcs, with interspersed white arcuate playas.

Ridge preservation also varies depending on local conditions. Ridges submerged due to rising sea level, such as those in the Atlantic Ocean, are eroded more quickly and easily than ridges confined to basins in the arid, subaerial environment of the southwestern U.S. On Mars, any post-ocean environment with a thin, water-poor atmosphere and no running water on the surface might be expected to resemble the better preservation environment of the U.S. southwest. Alternatively, aeolian activity operating for three-plus billion years could plausibly rework sand ridges into dunes, no longer recognizable as coastal ridges.

Finally, a search for coastal ridges implicitly begins with the assumption that an ocean existed in a liquid state. For example, a frozen ocean (Lucchitta et al., 1986; Kreslavsky and Head, 2002a), or at least an ocean with frozen margins, would be free from wave action and along-shore transport, and would therefore be unlikely to display similar coastal landforms to those observed along the margins of standing bodies of liquid water. The presence or absence of coastal constructional landforms along the margins of the northern lowlands can help constrain whether any ocean existed on Mars, and if so, whether it remained liquid or quickly froze.

2.2. *Data sets used in this study*

Considering the range of scales at which coastal constructional landforms are observed to occur on Earth (tens of meters to 1–2 km in width), MOC narrow angle (NA) and THEMIS visible (VIS) images are utilized in an orbital image survey for similar features on Mars. The combination of their areal coverage (∼2–5 km wide and up to 3 km long) and resolution (∼2–20 m/pixel) make MOC NA images better suited for identification of landforms in the tens to hundreds of meter scale, whereas THEMIS VIS images (∼10–20 km wide × 50–120 km long, with a resolution of ∼19–38 m/pixel), are better suited for identification of landforms at the kilometer scale.

Every THEMIS VIS and MOC NA image released to date that crosses, or is located near either the Arabia or Deuteronilus "shorelines" within both study regions is utilized. In total, eliminating images with significant data gaps and those of poor quality, 224 THEMIS VIS images and 502 MOC NA images of the Chryse/Arabia region and 223 THEMIS VIS and 223 MOC NA images of Isidis Planitia were surveyed (Fig. 4). Each image was downloaded and processed using the USGS ISIS software, geo-referenced, and placed in a GIS database containing the Viking MDIM 2.1 and the 128 pixel/degree gridded MOLA data.

Previous authors have noted the challenge of identifying coastal landforms from the air, let alone from orbit (Malin and Edgett, 1999; Clifford and Parker, 2001). In particular, identification of coastal constructional features such as ridges in aerial photographs of the Earth is aided by the presence of vegetation, which varies across terrain due to local properties such as soil porosity, permeability and slope. For example, within Spring and Long Valleys, Nevada, the sites of two paleo-lakes containing well-preserved barrier ridges, brushes preferentially occupy the regions between the ridges, whereas the ridges themselves tend to be sparsely covered by shallow-rooted vegetation such as grasses. As such, the ridges appear dark in aerial photographs, separated by bright bands (Fig. 3b). The absence of vegetation on Mars may thus serve as a hindrance to identification of coastal constructional landforms in images. One method of overcoming this challenge is to search for subtle, linear features in areas dominated by albedo variations. Particularly useful in such a search are MOC narrow angle images of our study regions, since the high sun angle for images at these latitudes tends to emphasize albedo differences across the terrain.

An additional method used to try and overcome the difficulties of identifying coastal ridges in satellite photos without the aid of vegetation, is to supplement the image analysis with a survey of raw MOLA profiles. Therefore, MOLA profiles across each "shoreline" within both study areas are examined, in search of laterally continuous ridge-like features of comparable scale to those observed on Earth. A comparison is made between these MOLA profiles and profiles across paleoshorelines from Spring and Long Valleys, Nevada (Zimbelman and Irwin, 2005) acquired using a Differential Global Positioning System (DGPS) (Zimbelman and Johnston, 2001). If coastal ridges are present on Mars near the mapped shorelines, but are not readily apparent in orbital images due to the absence of vegetation, or dust obscuration, they may be recognizable within the MOLA topographic data set.

3. THEMIS and MOC examination

As exemplified by the starkly different interpretations drawn by Malin and Edgett (1999) and Clifford and Parker (2001) of the same MOC image, it is apparent that different researchers are likely to arrive at different conclusions despite assessing the same data. As such, a primary purpose of this project is to provide an accounting of all features near previously identified global "shorelines" that might reasonably be interpreted as coastal constructional landforms, thereby allowing the reader the opportunity to judge for him or herself whether such features are indeed convincing.

In the descriptions that follow, extensive visual documentation is provided of the variety of ridges observed along both the Arabia and Deuteronilus shorelines, in both study regions, in both the THEMIS and MOC data sets. In Fig. 4, footprint maps are provided for all images analyzed in the survey, labeled with some images presented in later figures.

Identification of ridges that might possibly be interpreted as coastal landforms is complicated by the presence of wrinkle ridges (Golombek et al., 2001; Watters, 2004) and transverse aeolian ridges (e.g., Wilson and Zimbelman, 2004), both abundant in our study regions. Where ridges are observed that are clearly identified as wrinkle ridges or some form of aeolian construct, they are excluded from consideration as possible coastal landforms. Examples of these types of features, at both the THEMIS and MOC scales, are given in Fig. 5.

Tables A.1 and A.2 in Appendix A list all images analyzed that display ridges not immediately dismissed as either wrinkle or aeolian ridges. These tables list each image by number, along with their spatial resolution, a brief description of where in the image the ridges are located, and an assessment of whether these ridges constitute reasonable candidates for coastal landforms.

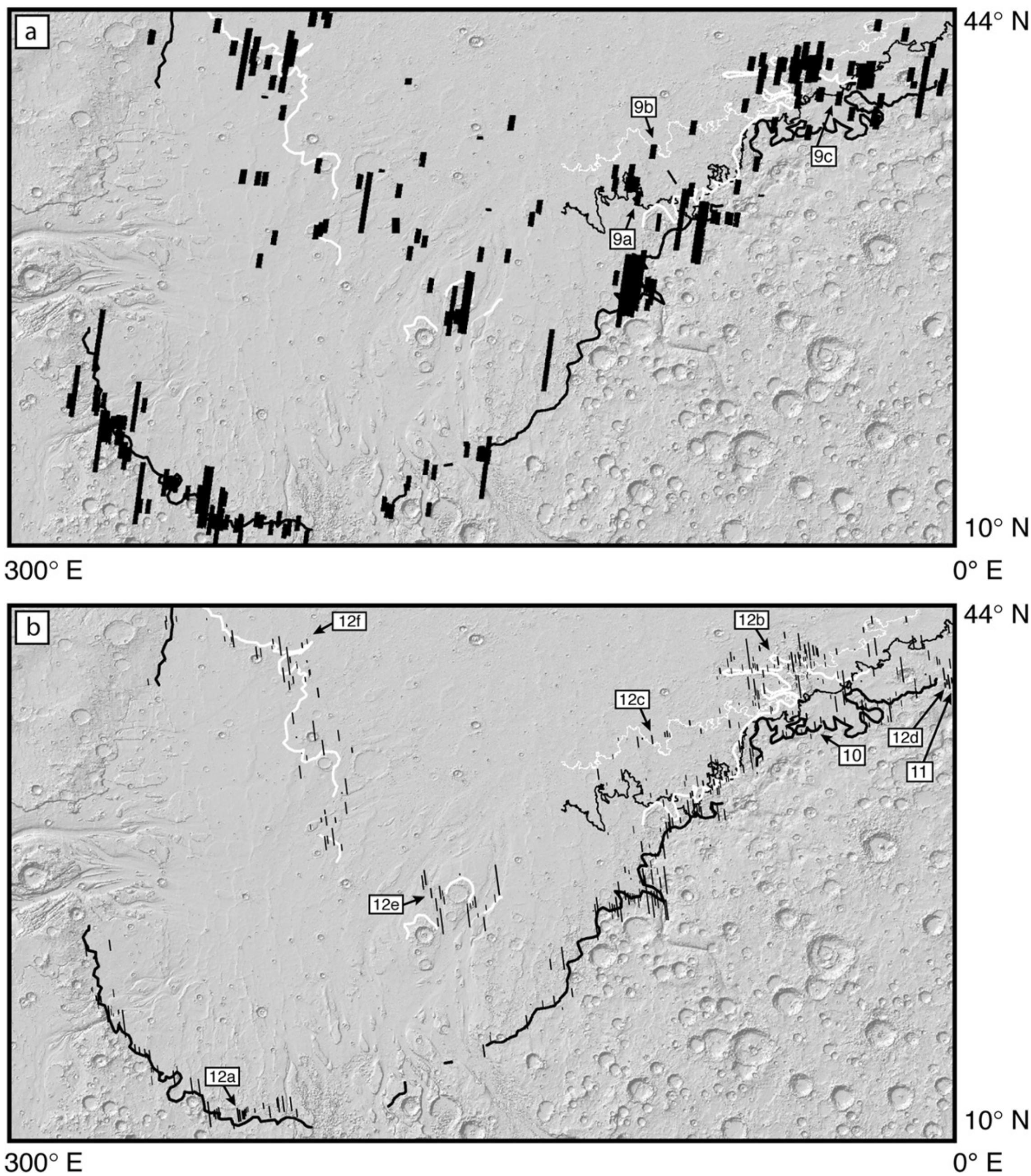

Fig. 4. Footprint maps for the two study regions, showing locations of all THEMIS VIS and MOC NA images analyzed in Chryse Planitia/Arabia Terra and Isidis Planitia. For the Chryse Planitia/Arabia Terra region, the thick black line indicates the Arabia "shoreline," the thick white line the Deuteronilus "shoreline," the thin black line the −4000 m contour, and the thin white line the −4200 m contour. For Isidis Planitia, the black line indicates the Arabia "shoreline" and the white line the Deuteronilus "shoreline." Labeled boxes indicate images shown in subsequent figures. (a) Chryse Planitia/Arabia Terra THEMIS VIS footprints. (b) Chryse Planitia/Arabia Terra MOC NA footprints. (c) Isidis Planitia THEMIS VIS footprints. (d) Isidis Planitia MOC NA footprints.

3.1. Chryse Planitia/Arabia Terra

As noted earlier, Webb (2004) suggests that within Arabia Terra, the Deuteronilus "shoreline" may be two separate shorelines approximated by two contours, one at −4000 m and the other at −4200 m (see red and yellow lines in Fig. 2a). Therefore, in the Arabia Terra portion of our survey, in addition to analyzing images that are on or near the "shorelines" as mapped by Clifford and Parker (2001), we further analyze those images located on or near the −4000 and −4200 m contours. Also, as noted by Carr and Head (2003), in the Chryse/Arabia region the southern margin of the Vastitas Borealis formation is closely approximated by the Deuteronilus "shoreline." Consequently, an analysis of the Deuteronilus "shoreline" incorporates an analysis of the margin of what Carr and Head (2003) have interpreted as the sublimation residue from a lowlands-filling ocean.

Parker et al. (1993) used high-resolution (∼50 m/pixel) Viking images to examine in detail an ∼125 km × 350 km portion of the Cydonia Mensae region, in which they observed several curvilinear ridges (Fig. 6a, see Fig. 2a for location). The

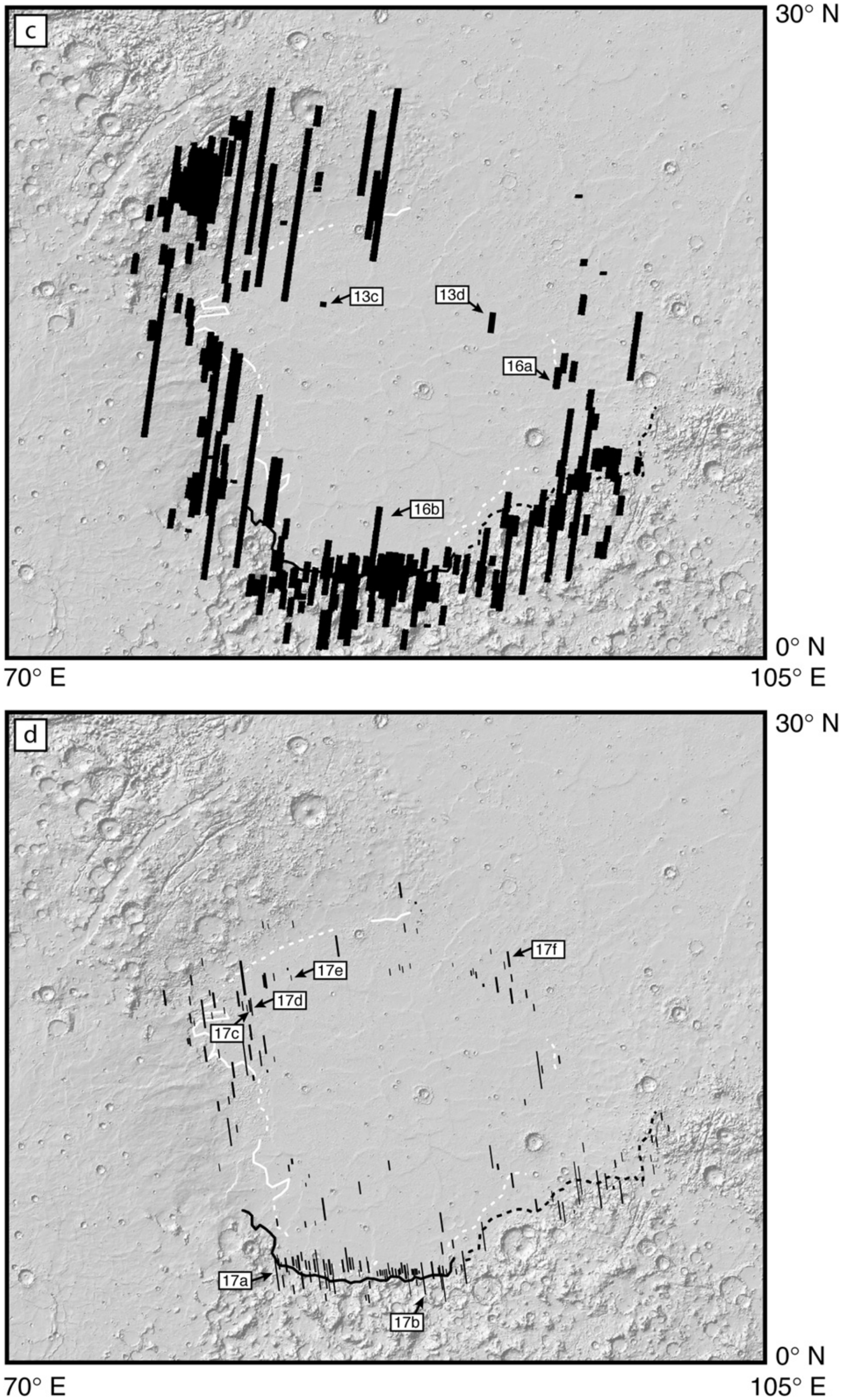

Fig. 4. (*continued*)

ridges were described as sharp-crested, arcuate and smooth, exhibiting no apparent correlation with regional structural grain. Located near both the Arabia and Deuteronilus "shorelines," these ridges, measuring 100 m to 2 km wide, and 2 to 50 km long, are closely associated with nearby massifs, sometimes enclosing them and other times extending between multiple smaller domes. Parker et al. (1993) interpreted these ridges as possible barrier ridges and spits.

Fig. 6a shows the trace of these ridges (thin black lines) on top of the high-resolution Viking mosaic originally used by Parker et al. (1993). Also displayed are the outlines of available THEMIS VIS (white boxes) and MOC NA (black boxes)

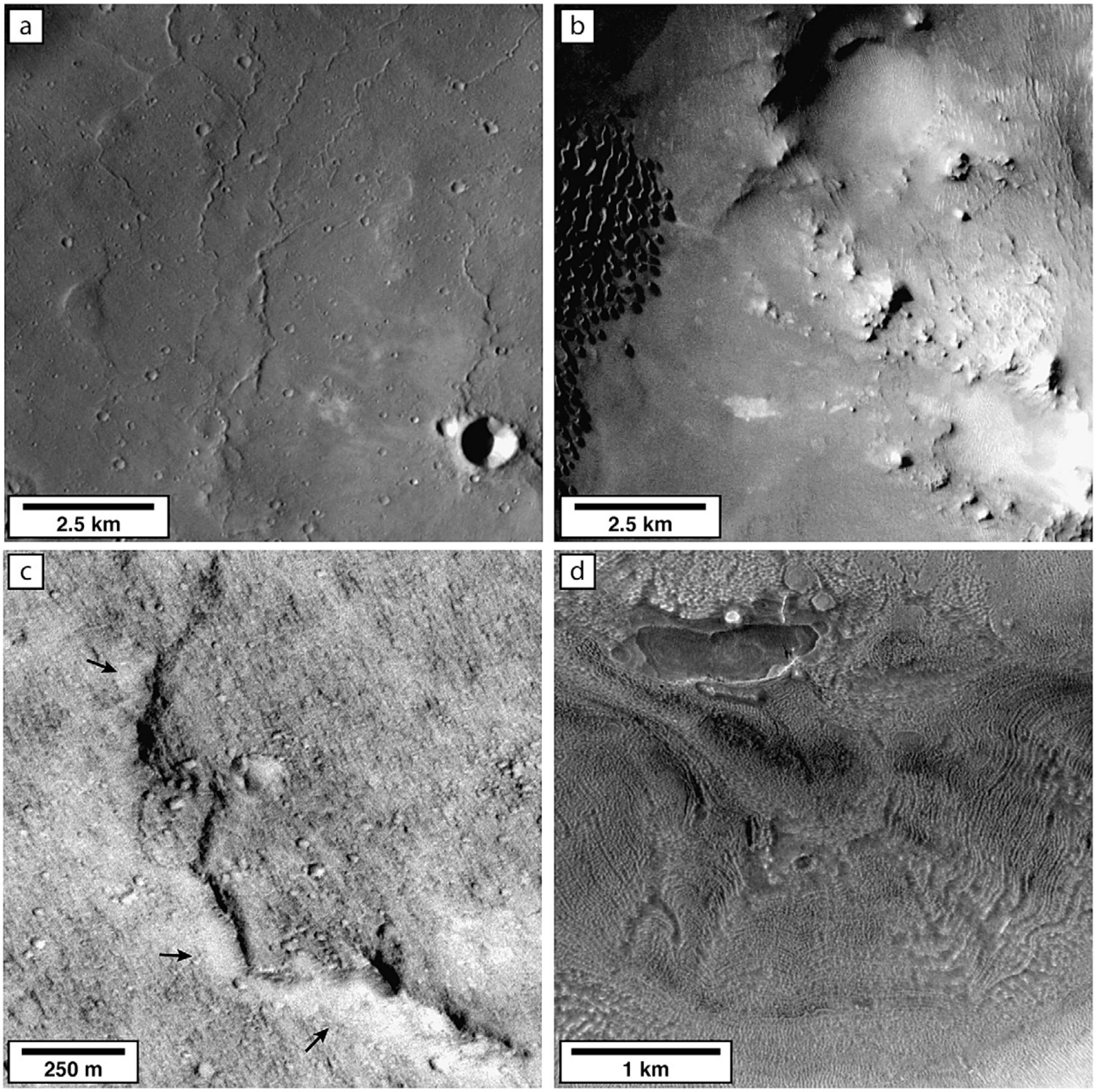

Fig. 5. Portions of THEMIS VIS and MOC NA images showing examples of wrinkle ridges and aeolian constructs within the study regions, used in our survey to distinguish ridges of these origins from candidate coastal ridges. (a) Wrinkle ridges in western Arabia Terra. THEMIS VIS image V05206008 (19 m/pixel). (b) Barchanoid (left) and linear (right) dunes in northern Isidis Planitia. THEMIS VIS image V13016004. (c) Wrinkle ridge (see arrows) in northwestern Arabia Terra. MOC NA image M0302720 (1.5 m/pixel). (d) Aeolian constructs, or aeolian eroded ice-rich material, resembling stacked ridges, located north of Arabia Terra. MOC NA image M2301482 (4.7 m/pixel).

images within this region, which are used to test the Parker et al. (1993) interpretations. Fig. 6b provides the locations of portions of THEMIS and MOC images within this region displayed in Figs. 7 and 8.

In the lower middle portion of Fig. 6 is a boot-shaped massif, an area around which Parker et al. (1993) described in detail. Near this massif, shown in Fig. 7a, two ridges are indicated with arrows, previously identified by Parker et al. (1993). The ridge near the middle of the image transitions into a scarp along the margin of the massif, a characteristic often observed among shorelines on Earth where sediment availability and coastal geometry vary (Adams and Wesnousky, 1998). Two mosaicked THEMIS VIS images provide comparable areal coverage of this region, but with improved 38 m/pixel resolution (Fig. 7b), revealing additional nearby ridges also associated with the massif (Fig. 7c). Again, at this higher resolution, examples of ridges transitioning into scarps are observed. Somewhat perplexing, however, is the apparent disappearance of one of the ridges when viewed at the MOC scale (Fig. 7d), and the revelation that another “ridge” is actually a scarp or an albedo boundary. Nonetheless, as described below, the ridges near the boot-shaped massif remain among the best candidates for coastal ridges observed in our survey.

Additional THEMIS (Figs. 8a–8c) and MOC (Figs. 8d–8f) images of the Parker et al. (1993) region capture some further examples of curvilinear ridges, including some previously un-

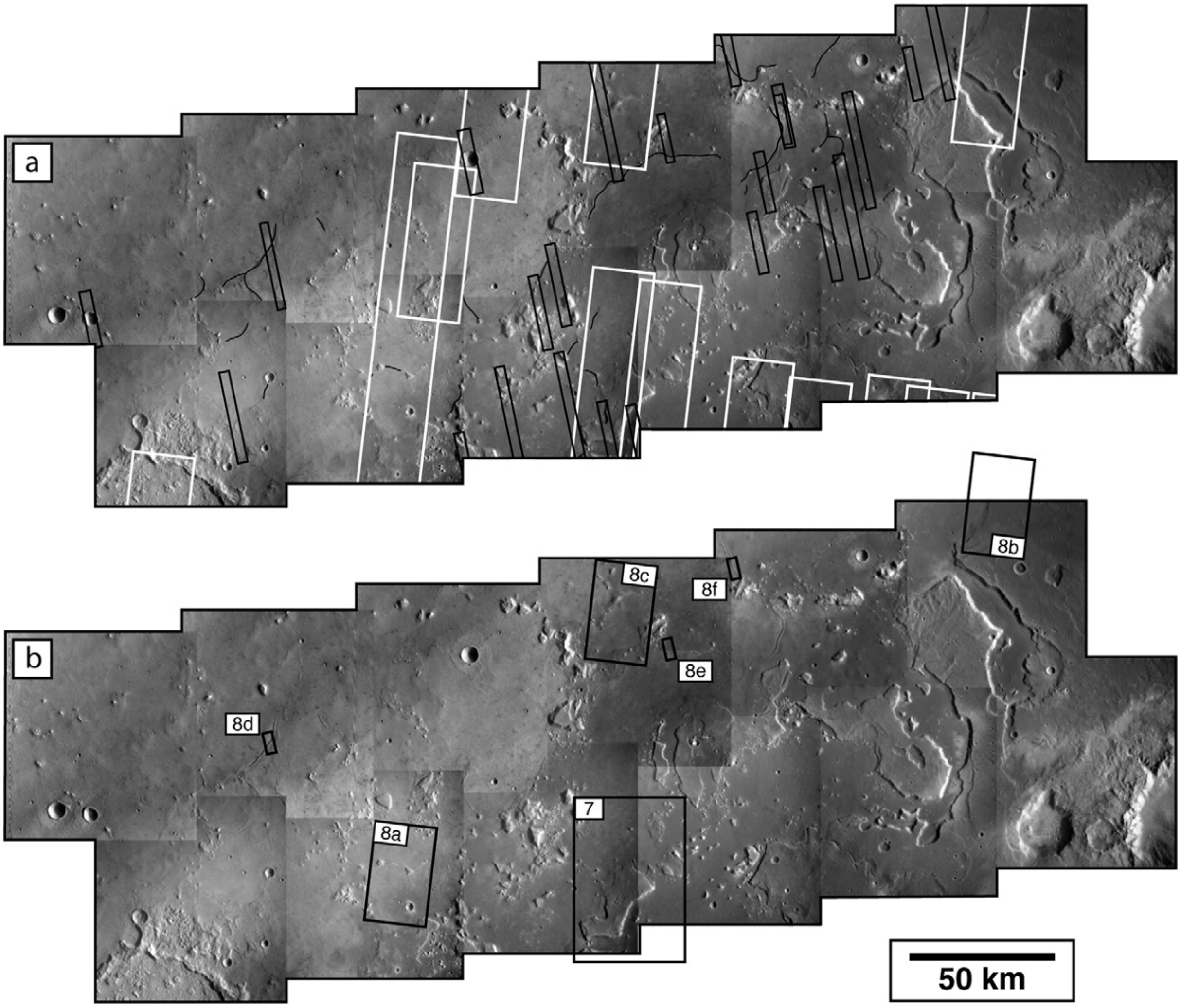

Fig. 6. (a) High-resolution Viking image mosaic of the Parker et al. (1993) study region in southwestern Cydonia Mensae. Thin black lines correspond to curvilinear ridges identified by Parker et al. (1993), and considered candidate coastal ridges. White boxes denote locations of all available THEMIS VIS images, and black boxes all available MOC NA images. Viking Orbiter images 227S04-15 (∼50 m/pixel). (b) Same region shown in (a), with black boxes denoting portions of THEMIS VIS and MOC NA images shown in Figs. 7 and 8, used to reexamine the curvilinear ridges of Parker et al. (1993).

seen in Viking images (see Fig. 6b for image locations). Fig. 8a displays either a single degraded ridge or two ridges, connected to nearby massifs, arranged in an arcuate manner. While similar in scale and morphology to the ridges seen in Fig. 7, the arcuate nature of the ridge(s) suggest a possible degraded crater rim origin. Fig. 8b shows the terraced margin of a plateau with an arcuate ridge splaying off the end (see arrow), somewhat similar to the ridges seen in Fig. 7, although considerably shorter. Fig. 8c shows a series of knobs and massifs, which in some places appear connected via narrow ridges (see arrows), and in other places appear surrounded by aprons. This relationship appears less consistent with spits and more comparable with lava flows or debris flows associated with the massifs. Within Figs. 8b and 8c, as well as throughout much of the region seen in Fig. 6, wrinkle ridges are observed.

Figs. 8d–8f reveal the variability in appearance among the curvilinear ridges at the MOC scale. For example, the ridges in Figs. 8d and 8e are smooth and flat-topped in places, and blockier with sharper peaks in other places, appearing wrinkle-ridge-like despite their lack of resemblance to wrinkle ridges at the THEMIS VIS scale. The ridge in Fig. 8e appears to decrease in width by a factor of two from the bottom left part of the image to the middle of the image. Also, the ridge in Fig. 8f appears considerably more degraded and less steeply sloped than those in Figs. 8d and 8e.

Of the remaining 212 THEMIS images outside the Parker et al. (1993) region three other examples of ridges connected to domes or massifs are identified. Two of these images show similar ridge-massif relationships to each other, an example of which is given in Fig. 9a. As can be seen, narrow ridges appear to enclose a cluster of massifs. These ridges are more irregular in appearance than the curvilinear ridges of Parker et al. (1993). Also, they appear to comprise the margin of a platform or plateau upon which the massifs are perched, suggesting that the ridges might simply be the leveed margins of a lava flow or the edges of debris flows associated with the massifs.

Fig. 9b, located just outside the Parker et al. (1993) region, reveals two ridges that appear somewhat similar to the

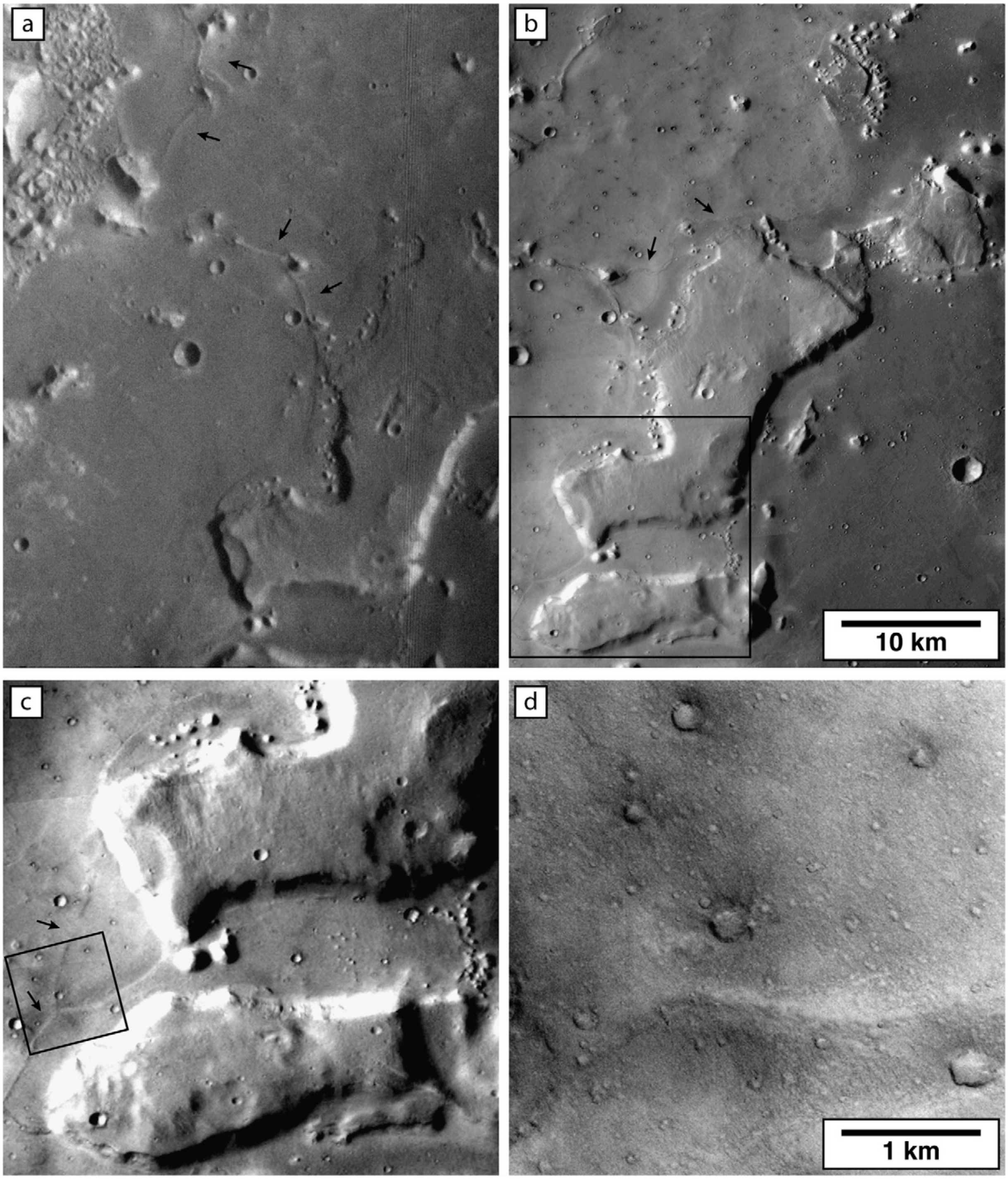

Fig. 7. (a) High-resolution Viking view of massif and surrounding region, examined in detail by Parker et al. (1993). Arrows indicate curvilinear ridges. Viking Orbiter image 227S09. See Fig. 6 for location (51 m/pixel). (b) THEMIS VIS mosaic of approximately the same region shown in (a), revealing additional ridges associated with the massifs, not previously seen. THEMIS VIS images V11634008 (38 m/pixel) and V11946011 (38 m/pixel). (c) Enlarged view of portion of (b), revealing additional ridges associated with the margins of the nearby massifs. Black box corresponds to (d). (d) Portion of MOC NA image E0902234 (6.4 m/pixel). Somewhat perplexing is the apparent disappearance of one of the ridges seen in (c), and the scarp-like appearance of what in (c) resembles a ridge.

above-described curvilinear ridges, although slightly narrower in width. The southern ridge appears to transition into the northern margin of a massif, whereas the northern ridge appears to extend between two other massifs. However, similar to the ridge seen in Fig. 8a, the arcuate nature of the northern ridge in Fig. 9b may imply a degraded crater rim origin.

Fig. 9c reveals a cluster of domes similar in size to those illustrated in previous THEMIS images. North of this cluster, the northern margin of which coincides with the −4200 m contour, are a few isolated massifs, one of which contains an arcuate ridge along its southern end (Fig. 9c, see inset). This ridge bears some resemblance to a looped barrier ridge.

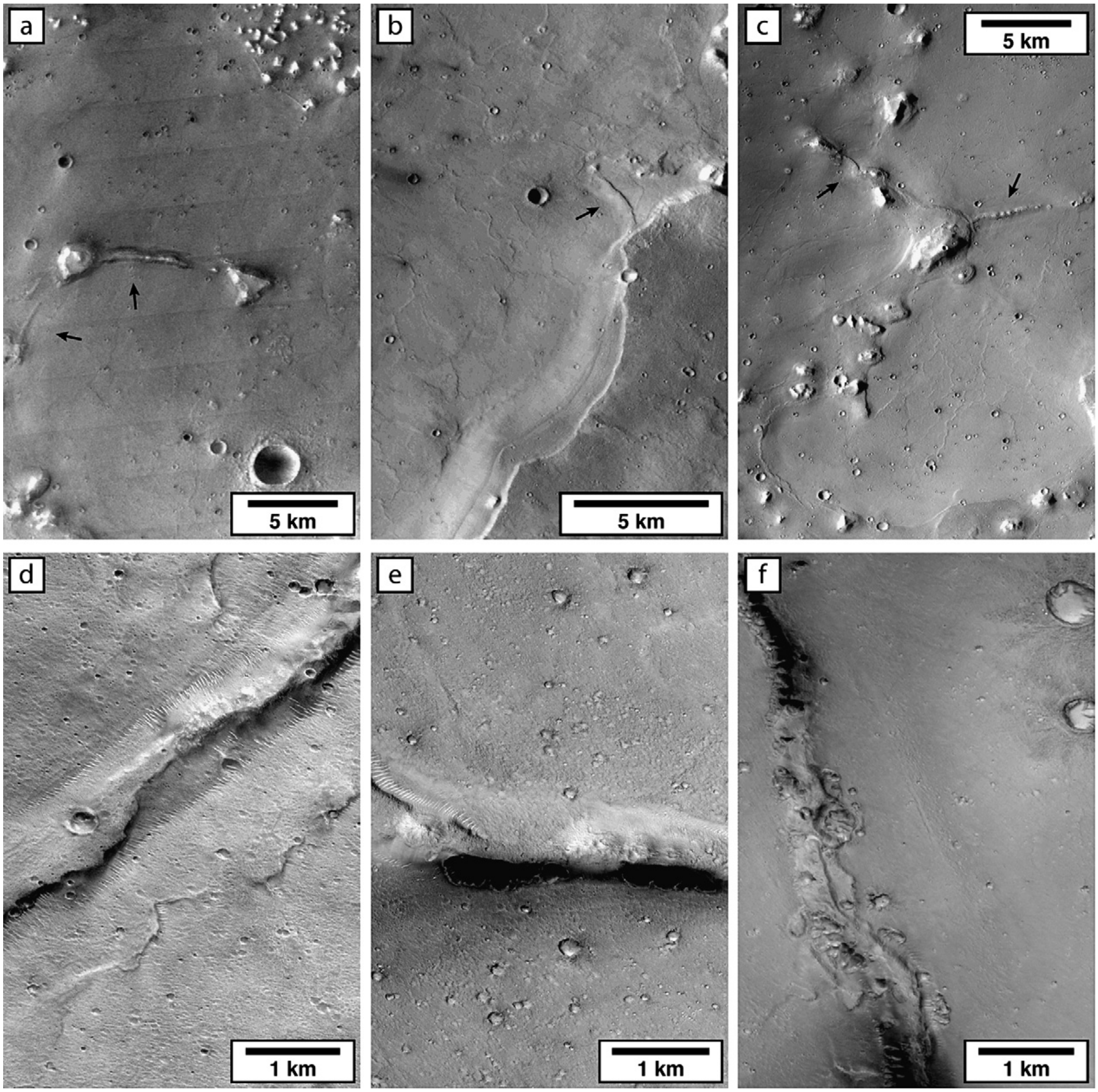

Fig. 8. Portions of THEMIS VIS and MOC NA images showing various examples of the Parker et al. (1993) curvilinear ridges from the Cydonia Mensae region. See Fig. 6 for locations. These images illustrate the variety in scale, plan form, and morphology observed among the ridges (see text). (a) THEMIS VIS image V06367023 (38 m/pixel). (b) THEMIS VIS image V05543011 (19 m/pixel). (c) THEMIS VIS image V05231008 (19 m/pixel). (d) MOC NA image E0301448 (3.1 m/pixel). (e) MOC NA image E0201419 (3.1 m/pixel). (f) MOC NA image E1900290 (4.8 m/pixel).

Looped barriers can form along the shore-facing margins of near-shore islets, as waves break around the islets and deposit sediment on their lee sides. In the case of the example in Fig. 9c, the looped ridge is on the −4200 m contour-facing side of the mesa, consistent with the direction waves would have traveled if the −4200 m contour once corresponded with an ocean coastline. However, this feature also bears resemblance to “moat-like” features seen elsewhere in the northern mid-latitudes, and thus may have nothing to do with a northern ocean and coastal processes. In all, none of the curvilinear ridges of Parker et al. (1993), nor the similar-type ridges identified in this study throughout the Chryse/Arabia region, appear to be reasonable candidates for coastal constructional landforms, with the single possible exception of the curvilinear ridge that transitions into the margin of the boot-shaped massif (Fig. 7).

At the MOC scale, Clifford and Parker (2001) traced a series of arcuate ridges within an image (M0704326) in the Arabia Terra region, which they compared to barrier ridges in Lake Bonneville in the western U.S. Shown in Fig. 10, these arcuate ridges are located within a northward facing alcove, and parallel adjacent higher standing terrain to the south. Measuring tens of meters wide and up to 3 km long, these ridges are somewhat similar in appearance to those observed in paleo-lakes in the western U.S. (compare with Fig. 3b), although they also bear similarity to a series of ridges present within an enclosed nearby impact crater located in the southern highlands (Fig. 11). The crater ridges, unlikely to have formed in association with a low-

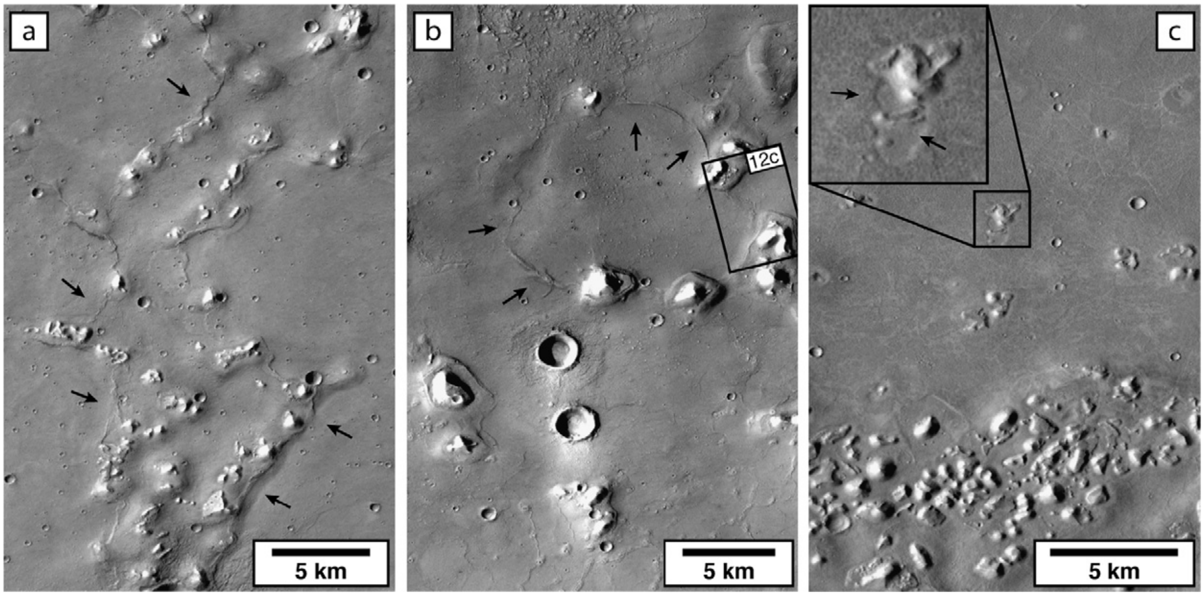

Fig. 9. Portions of THEMIS VIS images showing additional examples of curvilinear ridges within the Chryse Planitia/Arabia Terra region. (a) THEMIS VIS image V11422004 (19 m/pixel). Additional example of similar dome–ridge relationship is seen in image V09575018. (b) THEMIS VIS image V10486009 (19 m/pixel). (c) THEMIS VIS image V11172003 (19 m/pixel). Inset is magnified 2.5 times from original image resolution.

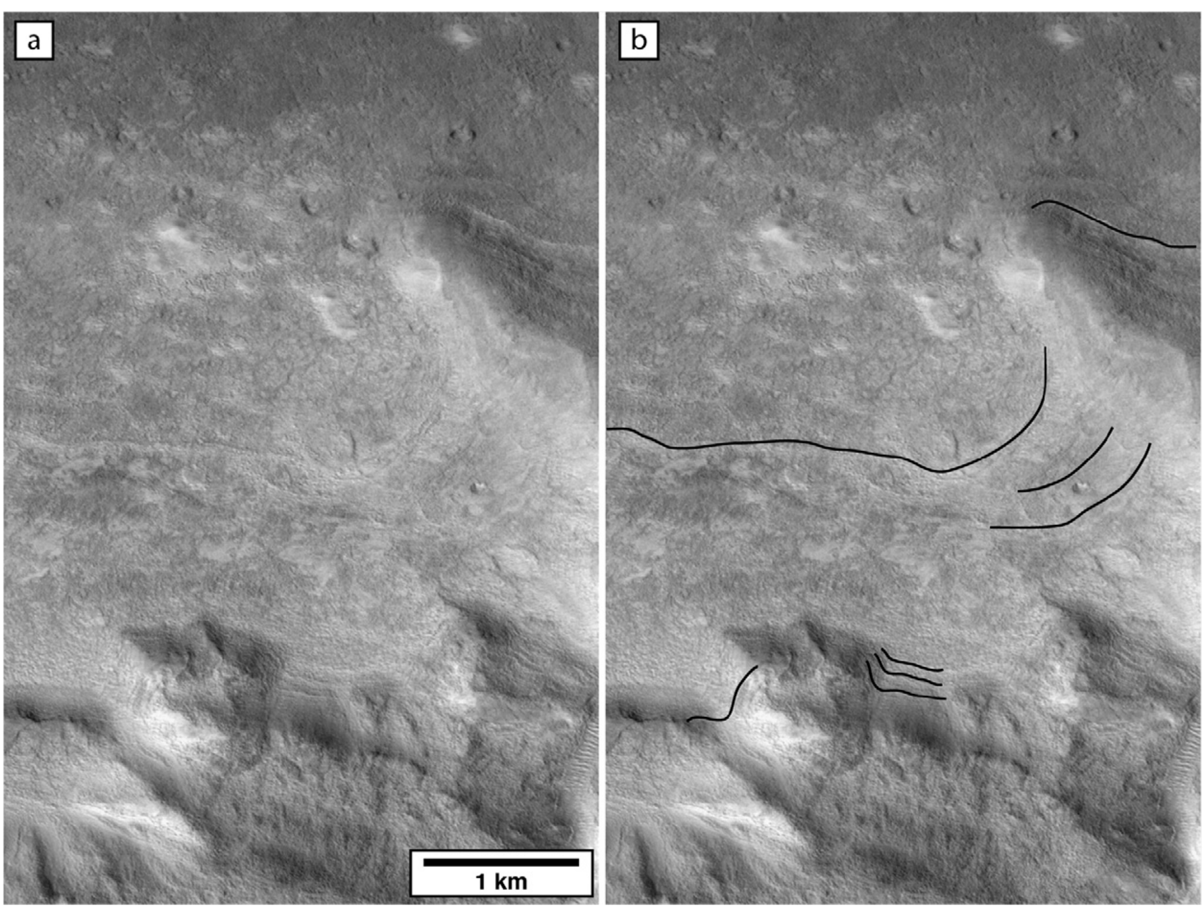

Fig. 10. Portion of MOC NA image M0704326 (4.6 m/pixel), located in Arabia Terra, and proposed by Clifford and Parker (2001) as displaying shoreline features associated with a paleo-northern lowlands-filling ocean. Highlighted in (b) are parallel, arcuate ridges, interpreted by Clifford and Parker (2001) as coastal constructional landforms.

lands ocean, may be attributable to ground ice flow (Squyres, 1979; Squyres and Carr, 1986) or wind action, suggesting that the ridges within Fig. 10 may themselves have formed independently of any putative ocean. Unfortunately, there are no

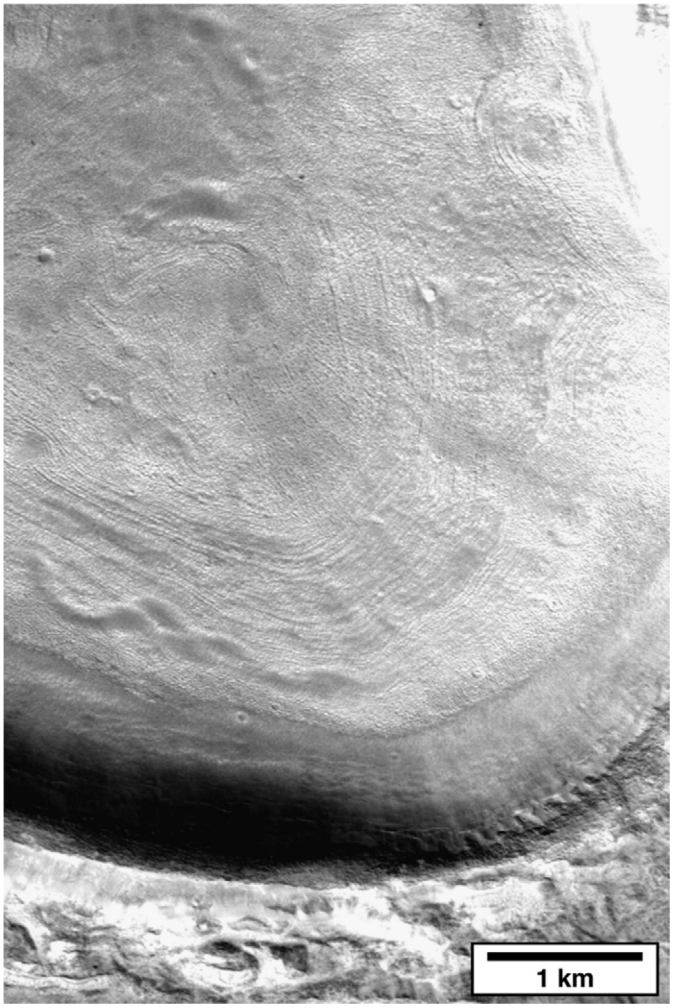

Fig. 11. Portion of MOC NA image R1402326 (6.5 m/pixel), located nearby Fig. 10 in Arabia Terra, showing multiple parallel, arcuate ridges located entirely within an enclosed impact crater. Such concentric crater fill (e.g., Squyres and Carr, 1986), somewhat similar to the ridges seen in Fig. 10, is not related to any putative standing body of water in the northern lowlands.

adjacent MOC images or even THEMIS VIS images to the image shown in Fig. 10, and THEMIS infrared is of inadequate resolution to determine the lateral continuity and areal extent of the observed ridges. Nonetheless, the ridges in Fig. 10 provide a reasonable template for stacked, closely spaced ridges that might possibly be interpreted as coastal constructional landforms.

Of the 502 MOC NA images analyzed in the Chryse Planitia/Arabia Terra region, only a small handful, 21, show any ridges or ridge-clusters that are not immediately dismissed as wrinkle ridges or aeolian landforms (Table A.1). Of these, six duplicate coverage of the same feature.

Figs. 12a and 12b provide examples of possible stacked ridges, somewhat similar in appearance to Fig. 10. Unfortunately the MOC resolution of Fig. 12a is too coarse relative to the observed lineations to determine whether they are indeed ridges or simply layering within the plateau occupying the southern and western portions of the image. Two additional occurrences similar to the region shown in Fig. 12a are observed by MOC, although each suffers from the same limits in resolution. Although the lineations in Fig. 12b were not immediately dismissed as aeolian landforms, there are clearly dunes or sand ripples occupying much of the top of the image, suggesting that the lineations in the cove may be aeolian in nature as well. Fig. 12c, showing an enlarged portion of Fig. 9b, reveals one of the two occurrences seen in MOC NA images of a ridge spanning the gap between two massifs, similar to some of the occurrences observed in THEMIS VIS images, although this ridge appears morphologically similar to wrinkle ridges.

Examples of the variety of generally non-stacked ridges observed in the region are shown in Figs. 12d–12f. As can be seen, some ridges occur in clusters with varying orientations (Fig. 12d), whereas some are isolated from other ridges (Figs. 12d, 12e). Also apparent is the variation in size and length, as well as orientation relative to the nearby "shoreline." Although these ridges are not immediately dismissed as wrinkle ridges, such an origin has not been ruled out. They could also have formed from a host of other tectonic or impact processes, such as exposed dike tips, inverted cracks, or eroded impact crater rims, all unrelated to the possible presence of a lowlands ocean.

In all, there are few MOC images near the mapped shorelines that reveal any ridges not immediately recognized as wrinkle ridges or aeolian constructs. Of the remaining images, there are none that reveal convincing evidence of coastal constructional landforms, with the possible exception of Fig. 10 (M0704326), previously identified by Clifford and Parker (2001).

3.2. *Isidis Planitia*

Ridges within the Isidis basin are both abundant and varied. Using Viking Orbiter images, Grizzaffi and Schultz (1989) mapped two units occupying the basin floor, a central hillocky unit and a surrounding ridged unit. Rounded and elongate knobs characterize the hillocky unit, measuring approximately 0.25 to 0.75 km wide, often arranged in isolated curvilinear chains (Fig. 13a). Some of these knobs were observed to be superposed with summit pits and elongate depressions, although the vast majority appeared to be pit-free in the Viking images. The ridged unit consists of arcuate, curvilinear ridges, measuring 0.5–1 km wide and 10–40 km long, often arranged in dense parallel systems. Among these ridges, some were observed that appeared continuous (Fig. 13b), whereas others were seen that appeared composed of aligned pitted knobs. At the THEMIS VIS scale it is apparent that most of the knobs are pitted (Fig. 13c), and that the ridges of the ridged unit that appeared to be continuous in Viking images, now are seen to display elongate summit depressions and may be composed of multiple pitted knobs (Fig. 13d). The ridges of the ridged unit have been described as "thumbprint terrain" due to their resemblance to the swirls in a fingerprint (Guest et al., 1977; Kargel et al., 1995). Previous investigators interpreted the knobs and arcuate ridges as volcanic in origin (Carr, 1981; Frey and Jarosewich, 1982) or as pingos (Parker et al., 1993). Instead, Grizzaffi and Schultz (1989) favored a sedimentary origin associated with a thick, ice-rich deposit occupying the Isidis

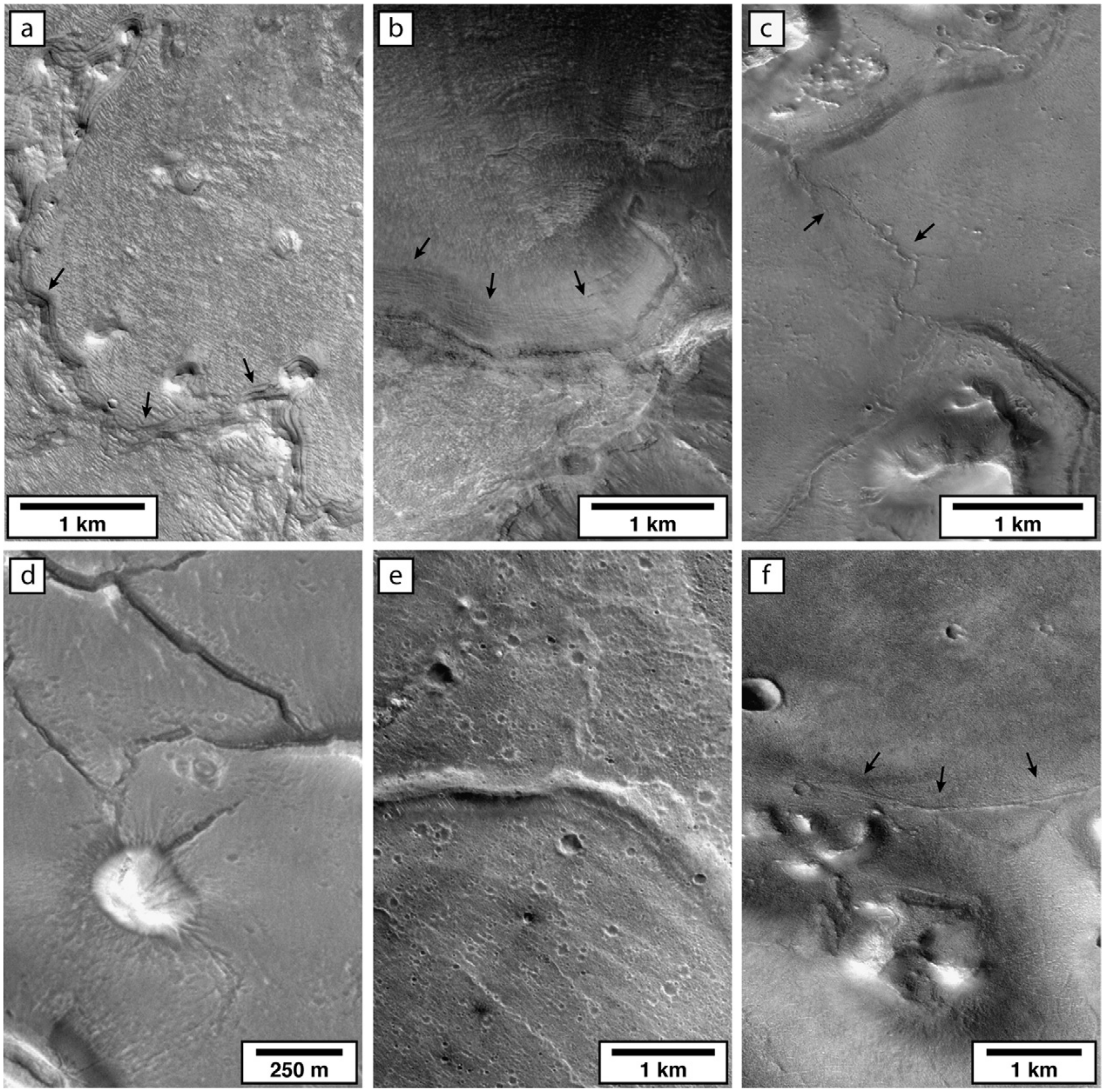

Fig. 12. Portions of MOC NA images from Chryse Planitia/Arabia Terra, showing examples of possible stacked ridges (a and b), curvilinear ridges (c), and the majority of other ridges observed near the mapped "shorelines." (a) MOC NA image E1002709 (4.6 m/pixel). (b) MOC NA image M1700389 (4.6 m/pixel). (c) MOC NA image R1100209 (4.8 m/pixel). (d) MOC NA image R1600661 (1.6 m/pixel). (e) MOC NA image E2300131 (6.3 m/pixel). (f) MOC NA image R0902829 (4.9 m/pixel).

basin, interpreting the domes and arcuate ridges as moraines, some of which were previously ice-cored.

In addition to the domes and arcuate ridges, an elongate ridge type was described, originating within the ridged unit and extending outward into a surrounding smooth annulus unit. These elongate ridges are distinct from the arcuate ridges in that they are sinuous, longer, and appear at Viking scale to lack any superposing pits. Grizzaffi and Schultz (1989) considered these ridges possible eskers. THEMIS VIS images suggest that some of the elongate ridges do in fact display superposing pits or depressions, and that they bear sufficient resemblance to the arcuate ridges to suggest a common formational process.

Based on the above THEMIS observations, neither the arcuate ridges of the ridged unit nor the elongate, sinuous ridges with summit depressions now seem to be reasonable candidates for coastal constructional landforms. Their pitted summit/elongate summit depressions, as well as their being comprised of individual domes, suggest that these ridges are morphologically distinct from terrestrial barrier ridges and other coastal landforms. Alternative hypotheses, such as the glacial model of Grizzaffi and Schultz (1989) or the volcanic landform model of Frey and Jarosewich (1982), are more attractive alternatives.

Parker et al. (1993) highlighted approximately twelve ridges or ridge portions in northwestern Isidis, located within the ridged unit, as candidate barriers and spits, primarily due to their arcuate nature, size, and location near the margin of a hypothesized ocean (thin black lines in Fig. 14a, see Fig. 2b

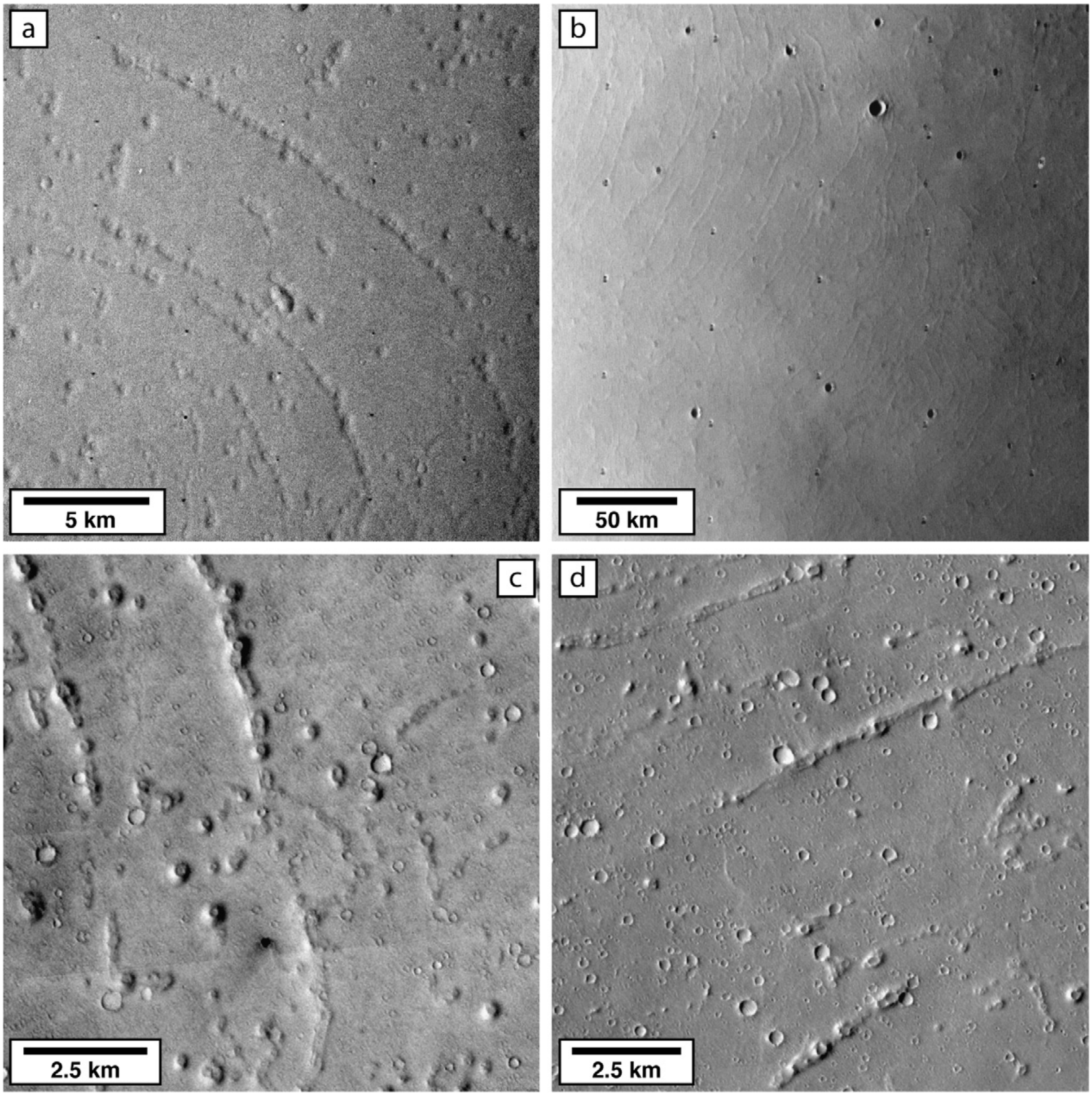

Fig. 13. (a) Portion of Viking Orbiter image 150S23 (29 m/pixel), showing knobs from the hillocky unit of Grizzaffi and Schultz (1989). At this resolution, a few knobs appear to display summit pits, although the vast majority of knobs appear pit-free. (b) Portion of Viking Orbiter image 67B55 (220 m/pixel), showing "continuous" ridges from the ridged unit of Grizzaffi and Schultz (1989). (c) Portion of THEMIS VIS image V01807007 (18 m/pixel), showing an enlarged view of the bottom right portion of (a) and the region to its south. Nearly every knob in fact displays a pitted summit. (d) Portion of THEMIS VIS image V11418009 (18 m/pixel), showing an enlarged view of lower central region of (b). This view reveals that the "continuous" ridges in fact appear to be composed of multiple individual pitted knobs, or to be transitional between pitted knobs and a single, continuous ridge.

for location). Some of these ridges appear to be arcuate ridges from the ridged unit, others appear to be scarps at the margins of deposits, and yet others appear to be continuous ridges not previously identified as either arcuate ridges or elongate ridges. None appear to be among the elongate, sinuous ridges.

Fig. 14a shows all available THEMIS VIS (white boxes) and MOC NA (black boxes) images of the Parker et al. (1993) region. Fig. 14b indicates portions of these images used in following figures. Three of the Parker et al. (1993) ridges are covered by THEMIS VIS images, two of which are also covered by MOC NA images (Fig. 14). A fourth ridge is also covered by a MOC NA image.

One of the "ridges," shown in Fig. 15a, is revealed by THEMIS to be a scarp, and therefore does not appear to be a reasonable candidate for a coastal ridge. The black box in Fig. 15a corresponds with a close-up MOC view (Fig. 15d), within which the scarp is not easily distinguishable. Fig. 15b reveals two narrow, relatively closely spaced ridges, associated with nearby domes, and which appear to merge to the north into a single ridge. At MOC scale (Fig. 15e) they appear shallowly sloped with a thin, sharp crest, and in places appear discon-

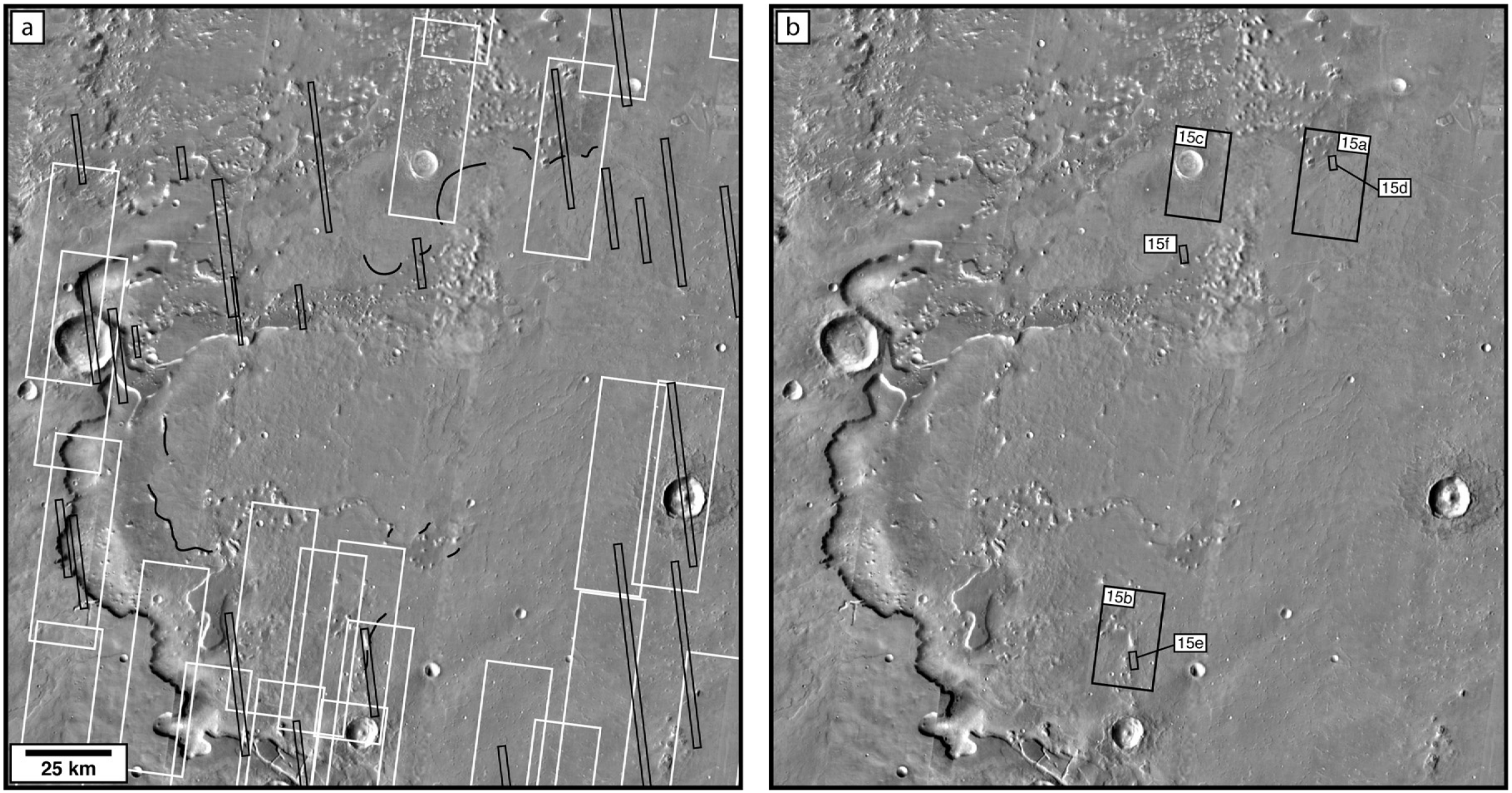

Fig. 14. (a) THEMIS daytime IR mosaic of the Parker et al. (1993) study region in northwestern Isidis Planitia. Thin black lines correspond to curvilinear ridges identified by Parker et al. (1993), and considered candidate coastal ridges. White boxes denote locations of all available THEMIS VIS images, and black boxes all available MOC NA images. Mosaic composed of THEMIS IR images I01932008, I03405047, I05652009, I07924020, I0787015, I08261014, I09509014, I09534022, I10158009, I11980006, I13253008, and I13540050 (∼100 m/pixel), with Viking MDIM 2.1 used to fill small gaps. (b) Same region shown in (a), with black boxes denoting portions of THEMIS VIS and MOC NA images shown in Fig. 15, used to reexamine the curvilinear ridges of Parker et al. (1993).

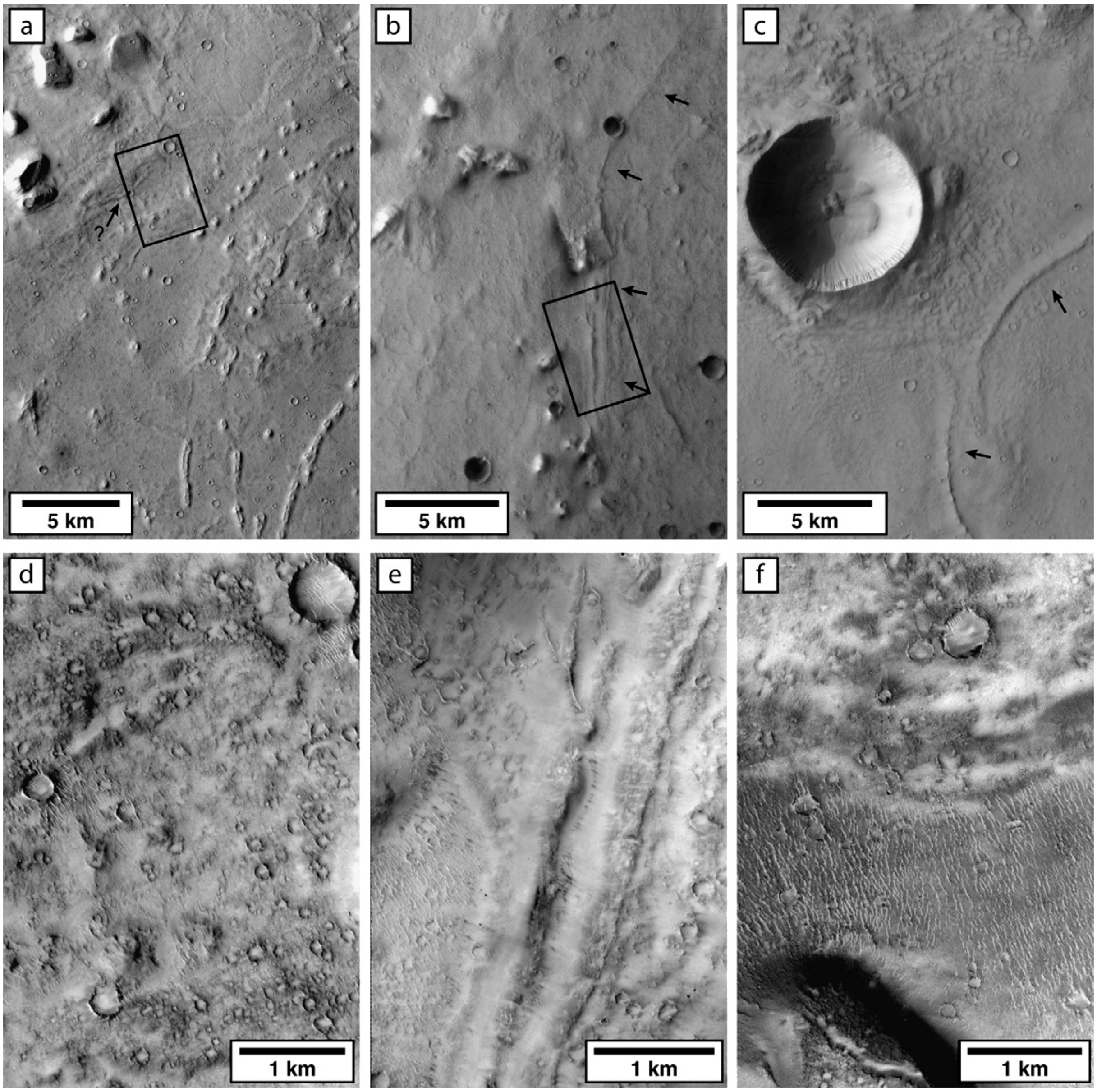

Fig. 15. Portions of THEMIS VIS and MOC NA images showing various examples of the Parker et al. (1993) curvilinear ridges from northwestern Isidis Planitia. See Fig. 14 for locations. While some of these ridges are continuous, others appear composed of aligned pitted knobs, some appear to be scarps, and others are simply a sharp textural difference observed across the terrain. Boxes in (a) and (b) correspond with enlarged MOC views shown in (d) and (e), respectively. (a) THEMIS VIS image V11980007 (18 m/pixel). (b) THEMIS VIS image V14139013 (18 m/pixel). (c) THEMIS VIS image V12604006 (18 m/pixel). (d) MOC NA image R0401310 (6.2 m/pixel). (e) MOC NA image E0101889 (4.5 m/pixel). (f) MOC NA image M1500469 (3.0 m/pixel).

tinuous. They do not appear to be wrinkle ridges or aeolian landforms, and may appear morphologically similar to some terrestrial coastal ridges. Fig. 15c reveals two ridges that together form an arcuate layout, although rather than joining, they parallel each other at their ends, suggesting that they probably are not remnants of a crater rim. Lastly, in Fig. 15f, one of the "ridges" is observed not to be a ridge at all, but to instead correspond with a texture shift along the terrain, perhaps associated with a scarp. To summarize, the vast majority of ridges previously identified by Parker et al. (1993) as possible coastal ridges do not remain reasonable candidates when observed with THEMIS VIS and MOC NA images, with the possible exceptions of those ridges in Figs. 15b, 15c, and 15e.

Throughout the rest of the Isidis basin, outside the Parker et al. (1993) region, our THEMIS VIS survey reveals only a few occurrences of ridges associated with the mapped shorelines. All but one of these occurrences are dismissed as wrinkle ridges (e.g., Fig. 16a). The exception (Fig. 16b) shows a series of crosscutting ridges, generally trending into the basin, which do not appear to be composed of individual domes.

At MOC scale many additional examples of aligned pitted domes and wrinkle ridges closely associated with the mapped shorelines are observed, as well as 13 ridges not dismissed as wrinkle ridges or aeolian features (Table A.2). Fig. 17a shows the only example of parallel, closely spaced lineations observed in the region, perhaps similar to the stacked barrier ridges ob-

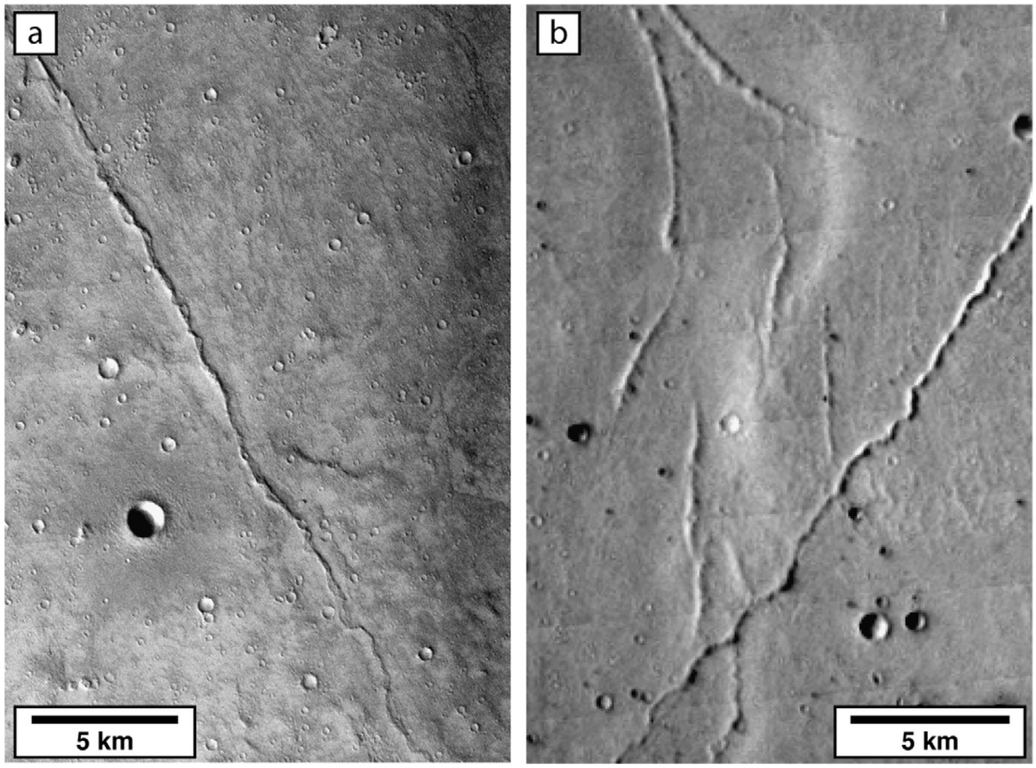

Fig. 16. (a) Portion of THEMIS VIS image V08198017 (18 m/pixel) showing a typical example of a wrinkle ridge observed along the "shorelines" in Isidis Planitia. (b) Portion of THEMIS VIS image V02431006 (72 m/pixel) showing the only example of ridges observed at the THEMIS VIS scale along the "shorelines" within Isidis Planitia, not immediately dismissed as wrinkle-ridges or aeolian landforms. Multiple, crosscutting ridges trend in a variety of directions.

served in Nevada (Fig. 3b). However, as with the features observed in Chryse/Arabia (Figs. 12a and 12b) it is not possible to tell whether these parallel lineations are constructional ridges, or simply exposed layers.

Fig. 17b shows a narrow ridge that parallels the margin of a slope along its base. Lastly, Figs. 17c–17f show examples of isolated ridges of various scales, some with smooth summits (Figs. 17c), some with pitted summits (Figs. 17d), some with elongate summit depressions (Figs. 17e), and some that appear blocky and perhaps discontinuous in places (Figs. 17f). While the ridges shown in Fig. 17 are not dismissed as wrinkle ridges or aeolian constructs, none appear to be convincing candidates for coastal constructional landforms.

3.3. *Deuteronilus Mensae*

In addition to the primary clusters of candidate coastal ridges identified by Parker et al. (1993) within Chryse Planitia/Arabia Terra and Isidis Planitia, Parker et al. (1989) suggested that coastal ridges might be present within some of the fretted canyons of Deuteronilus Mensae. Specifically, they suggested the "ridges and swales" that appeared at Viking-scale to parallel the margins of some canyon walls might represent beach ridges or bars. THEMIS VIS views of the primary fretted canyon analyzed by Parker et al. (1989) reveal the "ridges and swales" to be part of viscous flow features (e.g., Squyres, 1978; Squyres and Carr, 1986) similar to glacial-like landforms recently identified elsewhere on Mars (Milliken et al., 2003; Head et al., 2006) (Fig. 18). Similar landforms are found throughout many of the Deuteronilus fretted canyons, while no ridges are observed that resemble coastal ridges.

4. MOLA examination

As discussed earlier, the absence of vegetation on Mars may hinder identification of coastal landforms in satellite photographs. If not for the presence of vegetation on Earth, ridges easily identified in aerial/satellite photographs might be overlooked. However, if one knows where to look, shoreline features and coastal ridges can be identified in other data sets, such as within topographic profiles.

Differential Global Positioning System (DGPS) profiles, gathered during ongoing field studies from glacial paleo-lakes in Nevada (Zimbelman et al., 2005; Zimbelman and Irwin, 2005), reveal distinctive attributes that are laterally continuous across multiple, parallel profiles. Three, approximately 1-km-long, roughly parallel DGPS profiles were obtained across a series of stacked barrier ridges in Long Valley, Nevada (Fig. 19). With ~20 m along track spacing between data points, these profiles exhibit distinctive bumps, broader swells, and tie points that correspond to distinct coastal ridges that are identified across multiple profiles.

These observations and techniques provide a basis by which raw MOLA profiles crossing the mapped "shorelines" can be used to search for possible coastal constructional landforms, largely absent from the spacecraft photo survey. Clearly the ~300 m along-track spacing of MOLA is of insufficient resolution to distinguish landforms similar to the smaller-scale

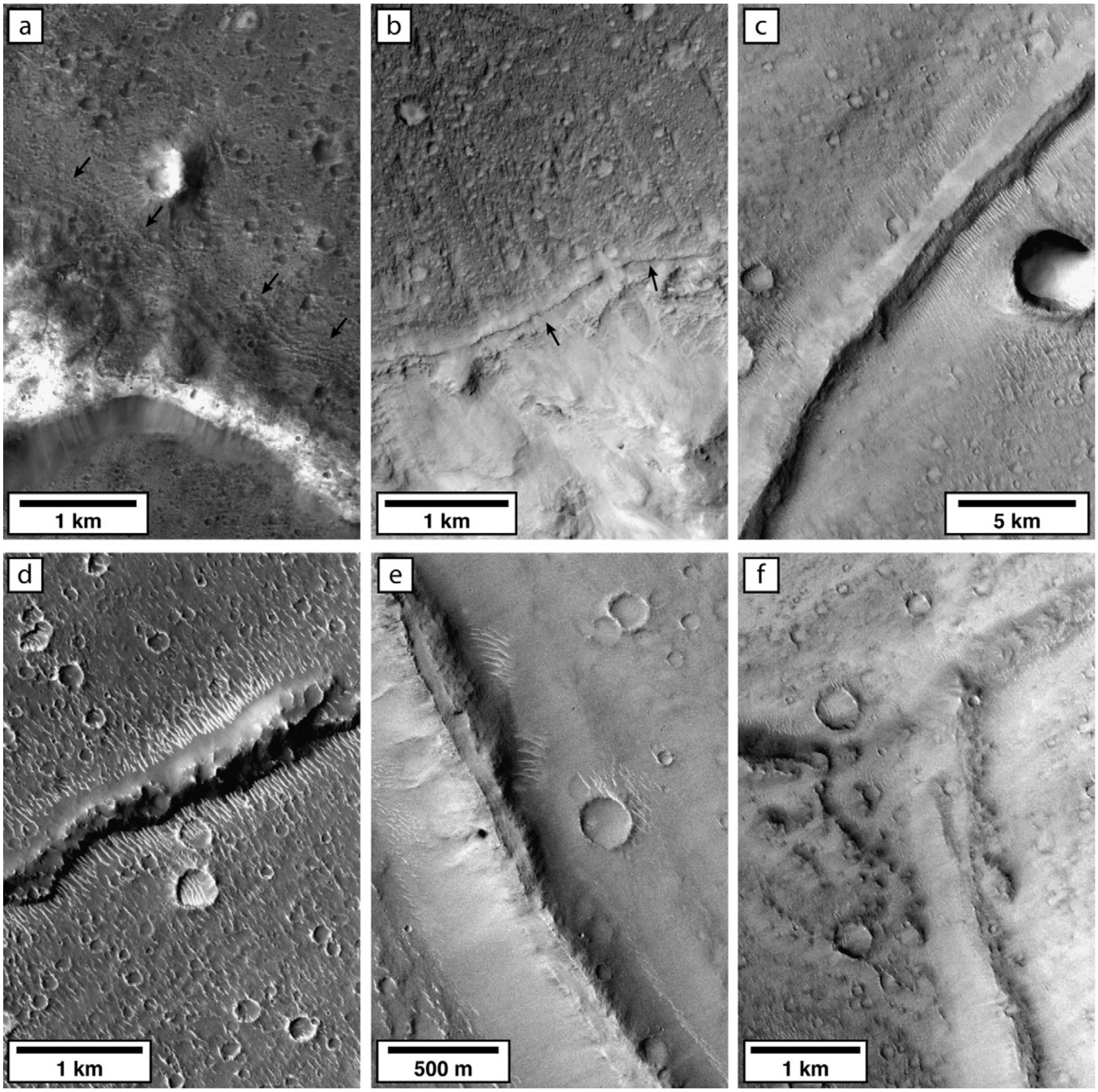

Fig. 17. Portions of MOC NA images from Isidis Planitia, showing a variety of ridges observed along the "shorelines," including possible stacked ridges (a), a ridge that parallels the margin of a nearby cliff (b), and multiple examples of isolated ridges displaying various morphologies and scales (c–f). (a) R0400177 (6.1 m/pixel). (b) E0300958 (5.8 m/pixel). (c) E2301442 (4.7 m/pixel). (d) M0902298 (5.9 m/pixel). (e) FHA00994 (1.5 m/pixel). (f) E0201040 (4.5 m/pixel).

features observed in the terrestrial profiles, but may be sufficient to distinguish the broader swells.

Raw MOLA profiles were collected at regularly spaced intervals of ∼75–100 km, along both "shorelines" in the Chryse Planitia/Arabia Terra and Isidis regions, as well as along the −4000 and −4200 m contours in the Arabia Terra area. For each profile a length extending 7.5 km upslope from, and 10 km down slope of, the corresponding "shoreline" was examined. For any profile that displayed features-of-interest (i.e., features resembling the ridges and valleys observed in the terrestrial profiles) adjacent profiles were collected and examined for lateral continuity of these features to distinguish isolated knobs from ridges (Fig. 20).

Although initial examination of the profiles returned multiple candidates displaying possible features-of-interest, upon further examination with adjacent profiles, none revealed convincing examples of laterally continuous ridges. For example, examination of the profiles shown in Fig. 20 reveal a series of bumps and valleys, similar to those seen in Fig. 19, although approximately an order of magnitude larger. It is even possible to begin identifying potential tie points among the profiles in Fig. 20, perhaps indicating the presence of laterally continuous ridges similar to those observed in Long Valley, Nevada. However, reference to the accompanying THEMIS infrared context image reveals that the bumps actually correspond to distinct knobs and mesas crossed by the three profiles, and not to multiple, parallel ridges. Despite all that MOLA has done to change our views and understanding of Mars, a more complete and conclusive search for coastal landforms utilizing topographic data may ultimately require a more extensive data

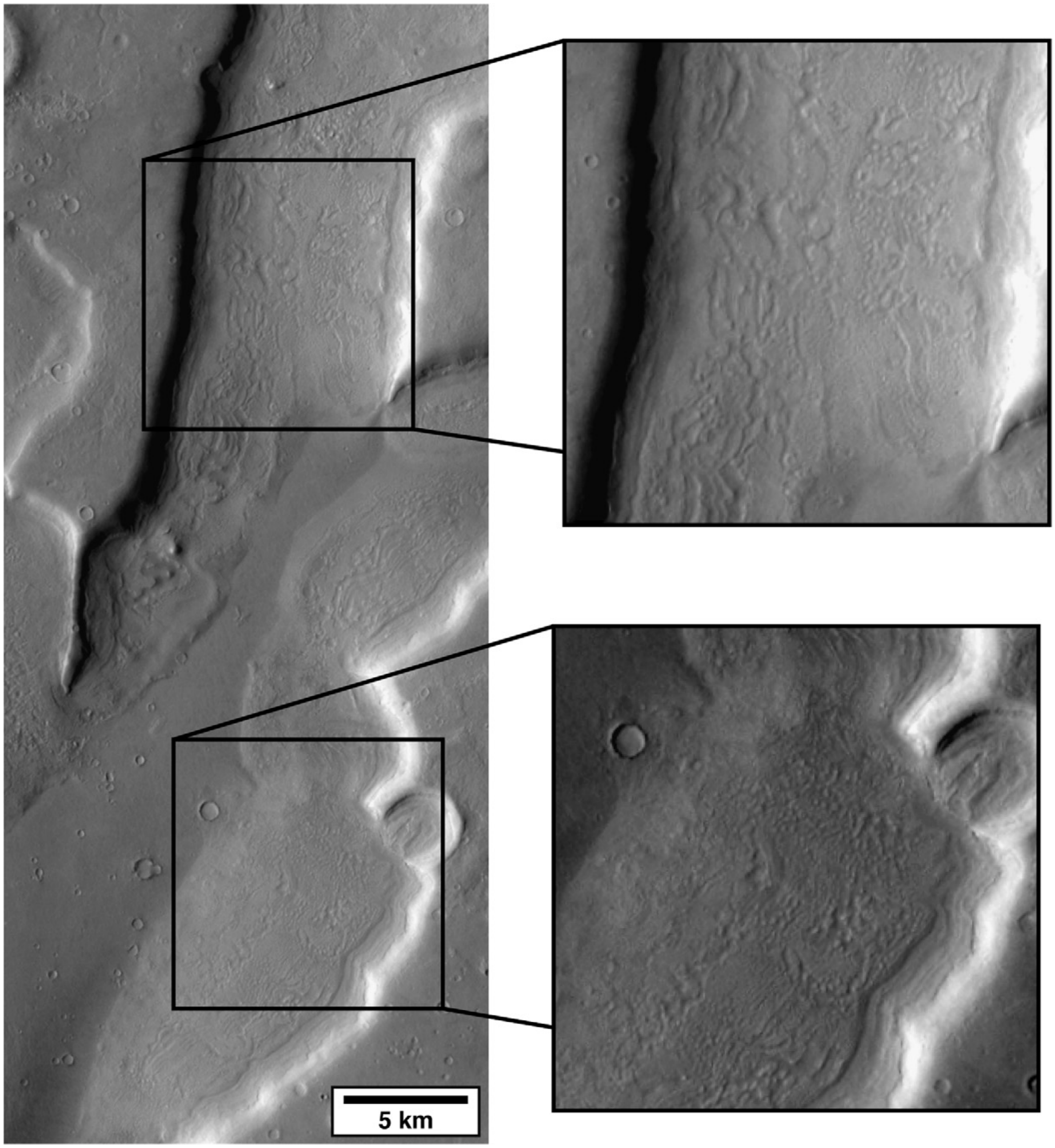

Fig. 18. Portion of THEMIS VIS image V11346007 (38 m/pixel), with enlarged portions revealing the floor of a fretted canyon in Deuteronilus Mensae. Seen along the floor is an otherwise smooth deposits displaying grooves, pits and possible streamlines, resembling viscous-flow features observed elsewhere on Mars (e.g., Milliken et al., 2003; Head et al., 2006).

set with closer along-track spacing than what is available with MOLA.

5. Summary and discussion

With the exception of those ridges seen in Figs. 7 and 10 from Chryse Planitia/Arabia Terra, and Figs. 15b and 15c from Isidis Planitia, no other ridges identified in close proximity to the mapped "shorelines" are reasonable candidates for coastal constructional landforms. The vast majority of ridges located near the "shorelines" are immediately dismissed as wrinkle ridges or some form of aeolian construct. The remaining ridges, including many previously considered possible coastal ridges by Parker et al. (1993), are more readily interpreted as remnants of crater rims, scarps, aligned pitted domes, or raised margins of debris/lava flows. As such, the paucity, and near total lack of candidate coastal constructional landforms found in association with the proposed shorelines of a northern lowlands ocean must place certain constraints on the possible existence of such an ocean.

Scenario 1: No ocean/large, standing body of water existed within the northern lowlands up to the level of the Arabia or Deuteronilus "shorelines." The absence of coastal constructional landforms could be interpreted as evidence against the

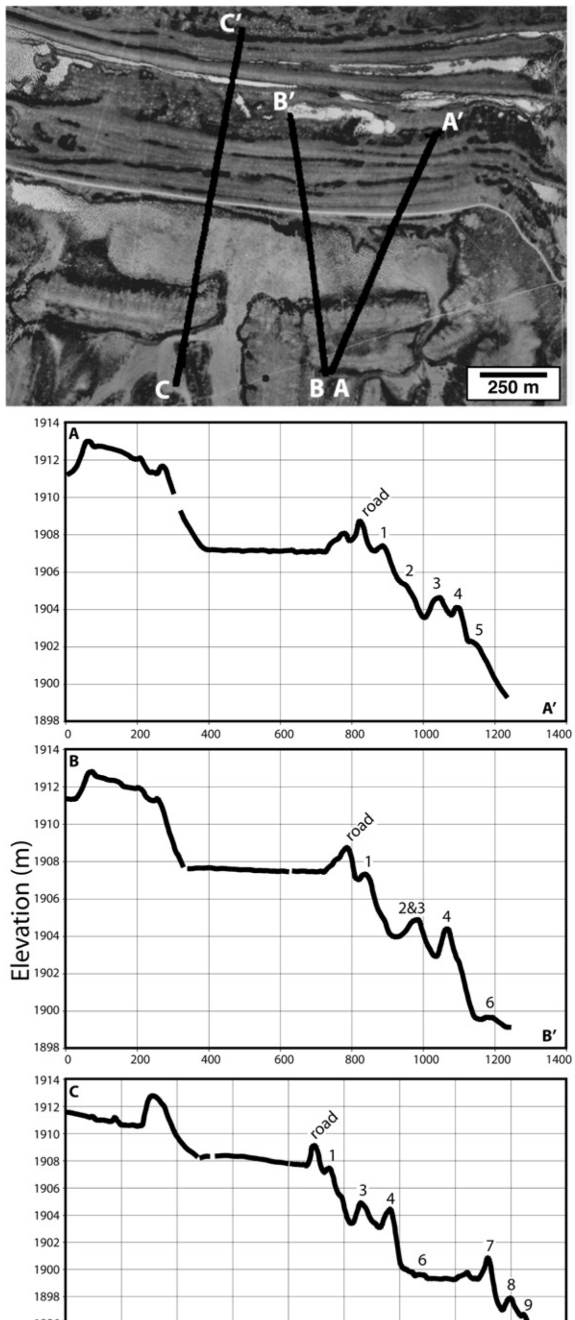

Fig. 19. Differential Global Positioning System profiles across paleo-shorelines within the southern region of Long Valley, NV (39.4° N, 115.3° W). Image is a portion of Digital Orthophoto (DOQ) data of the region. Scene is approximately 2.3 km wide. Profiles are characterized by approximately 20 m along-track spacing between gathered data points. Tie points are labeled that link the same ridge across multiple profiles. Occasionally ridges pinch out or merge.

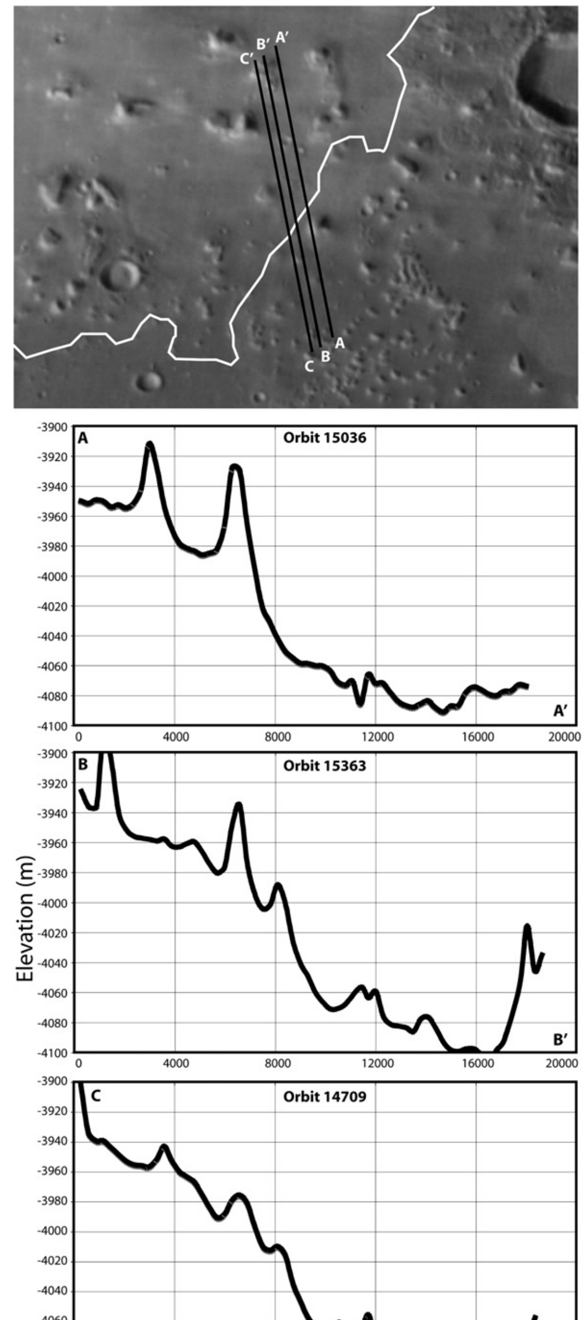

Fig. 20. Raw MOLA profiles across the −4000 m contour in Arabia Terra, considered by Webb (2004) as one of two regional still-stands of the Deuteronilus "shoreline." Image is a portion of THEMIS daytime infrared image I10311035. Scene is approximately 36 km across. Profiles are characterized by approximately 300 m along-track spacing. Although examination of the profiles suggests possible tie points among the observed bumps, similar to those observed in Fig. 19, reference to the context image reveals that the bumps actually correspond to isolated knobs and mesas, and not to laterally continuous ridges.

existence of oceans within the northern lowlands. However, since this study only focused on searching for such landforms near the Arabia and Deuteronilus "shorelines," this scenario would not preclude the possible existence of smaller standing bodies of water that perhaps did not occupy the entire northern lowlands, such as suggested by previous investigators (e.g., Scott et al., 1991, 1995). Further studies that search for coastal constructional landforms near the margins of proposed smaller bodies of water in the northern lowlands could help constrain this scenario.

Scenario 2: An ocean existed, however wave action, the agent responsible for the construction of coastal constructional landforms on Earth, was minimal to non-existent. Empirical studies have clearly shown that wave formation decreases considerably with decline in either atmospheric density or wind speed (Lorenz et al., 2005). Therefore, while atmospheric density may once have been great enough to support an ocean, it may have still been too thin to support substantial wave action. One complication with this scenario is that benches/scarps mapped as parts of the shorelines are thought to have formed via wave action (Parker et al., 1989, 1993; Webb, 2004). In this study we have not attempted to assess past interpretations of such features, although other investigators have suggested that observed benches and scarps along the contacts are not convincingly interpreted as shorelines (Malin and Edgett, 1999; Carr and Head, 2003). Additionally, recent modeling of martian wave energy by Kraal et al. (2006) indicates that scarp generation by wave-induced erosion of bedrock would be extremely difficult, even with conservative estimates of wind speed, shore slope, and substrate composition. Under the most favorable conditions modeled, scarps measuring only ∼5 m high were generated, well below the spatial resolution of all available martian image data sets, except perhaps MOC NA images. Clifford and Parker (2001) suggest that rather than being wave-eroded, the scarps associated with the mapped "shorelines" likely formed via erosional processes associated with an ice-covered or fully frozen ocean.

Scenario 3: An ocean existed, but sediment input was not significant enough to form coastal deposits. On Earth, sediment is regularly supplied to the oceans along their coasts via surface runoff and river discharge, as well as via wave-induced erosion of coastal bedrock, and is continually transported along shore and deposited as barrier-like features. On Mars, an ocean is often thought to have formed as the result of catastrophic release of groundwater associated with outflow channel development. In this scenario, beyond any initial sediment input from the channels, a regular exogenic sediment supply would have been non-existent. Also, as described above, Kraal et al. (2006) suggest that bedrock erosion would have been difficult even under favorable modeled conditions, implying minimal endogenic sediment contributed to constructional landforms via coastal erosion. As a consequence, even if wave action were sufficient to generate constructional landforms, there may not have been a large enough sediment supply necessary to construct such features. Without prolonged sediment re-supply, barriers exposed to wave action and along-shore currents will tend to erode. It is the continuous addition of sediment at one end, and removal at the other, which establishes equilibrium in the growth and decline of coastal constructional landforms (King, 1972). Therefore, while an initial sediment pulse from an outflow event might provide early sources of sediment for coastal ridge construction, without continued sediment re-supply, wave-induced erosion of these features would quickly lead to their destruction.

Scenario 4: An ocean existed, but readily froze, and over time sublimated. Lucchitta et al. (1986) initially proposed such a scenario, more recently expanded upon by Kreslavsky and Head (2002a), which could account for the absence of wave-related features. Again however, the interpreted wave-cut benches complicate the scenario, unless a non-wave-related mechanism for their formation is achievable with a frozen ocean. Indeed, while Parker et al. (1989, 1993) initially considered the "shoreline" scarps as wave-eroded features, Clifford and Parker (2001) suggest that the scarps and benches are more likely to be ice-induced erosional landforms. More recently, initial modeling of ice-filled craters suggests that pile-up and flow of ice along the crater margins could form terraces similar to those observed in many martian highlands craters (Barnhart et al., 2005). While admittedly at a different scale than a lowlands-filling ocean, these model results suggest a possible non-wave mechanism for generation of ocean-related scarps, while simultaneously accounting for the paucity of observed coastal constructional landforms. Application of similar modeling to the northern lowlands would be useful in determining the feasibility of this scenario.

Scenario 5: An ocean existed, and coastal constructional features formed in association with previously interpreted erosional features, but in the intervening time since their formation, they have nearly all been eroded away. For a Noachian ocean such a scenario may be reasonable, especially considering the greater erosion rates thought to be characteristic of this earliest period in Mars' history (Craddock and Maxwell, 1993; Golombek and Bridges, 2000; Golombek et al., 2005). Bedrock features such as scarps would be expected to resist erosion easier than constructional features such as barriers and spits, which on Earth tend to be composed of sand-to pebble-sized grains. However, coastal landforms resulting from a Late Hesperian or even early Amazonian ocean might be expected to be better preserved, not only due to the shorter period between formation and the present, but also because of the lower erosion rates across Mars during its post-Noachian history. Parker et al. (1989, 1993) initially suggested that their "shorelines" formed during the early Amazonian, whereas Clifford and Parker (2001) propose a Noachian-aged ocean, with shorelines dating to as far back as ∼4 Ga. The paucity of candidate coastal constructional landforms could be interpreted as favoring a Noachian-aged ocean over a younger one.

While each of the above scenarios is fully consistent with the available data, some appear more likely than others. For example, the outflow channels, if carved by water, must have resulted in ponded water of some volume for some period of time in the lowlands. Whether coastal landforms formed around these smaller-than-ocean-sized ponded bodies of water remains to be determined. Also, the modeling work of Kraal et al. (2006) suggests that even under the most favorable wave conditions, wave energies would be insufficient to produce erosional landforms recognizable in currently available satellite images. Since coastal constructional landforms on Earth tend to be of comparable scale to coastal benches, it seems quite likely than even if an ocean existed in the martian lowlands and formed coastal ridges, these ridges might also not be currently detectable. Whether sufficient sediment was available to form coastal ridges, whether such ridges formed and were later eroded, or whether an ocean existed in a frozen state, are all valid scenarios, as described above, but are less easily evaluated than Scenarios 1 and 2.

6. Conclusions

A focused search along previously mapped martian ocean "shorelines" within the Chryse Planitia/Arabia Terra and Isidis Planitia regions reveals a paucity of candidate coastal constructional landforms. Nearly all ridges associated with these shorelines, including those previously considered possible barriers and spits, are more readily interpreted as tectonic, impact, volcanic or aeolian landforms, and do not morphologically resemble terrestrial coastal ridges. Additionally, an assessment of the viability of using raw MOLA profiles to identify any putative coastal ridges not apparent in spacecraft images, indicates that the along-track and spatial resolutions of MOLA are inadequate to resolve such fine-scale landforms. This dearth in recognizable coastal ridges does not necessarily preclude the existence of northern-lowlands filling oceans during Mars' geologic history, but it does constrain the conditions under which any such ocean(s) might have existed.

Acknowledgments

We gratefully acknowledge a constructive review by Phil Christensen, as well as a detailed review by Tim Parker (who still likely disagrees with our conclusions). Discussions with and comments from Jim Head and Ross Irwin on an earlier version of the manuscript are much appreciated. We also wish to acknowledge extensive use of the wonderful THEMIS website (http://themis-data.asu.edu) supported by ASU. This work was supported by the Mars Fundamental Research Program (Grant NAG5-12746).

Appendix A

Table A.1
Chryse Planitia/Arabia Terra images with ridges not immediately dismissed as wrinkle ridges or aeolian constructs

Image #	Shown in	Res. (m/pixel)	Location of feature(s) in image	Candidate coastal ridge?
		Parker et al. (1993) region		
E0201419	Fig. 8e	3.07	Bottom	No
E0300904		4.58	Near top trending NE–SW	No
E0301448	Fig. 8d	3.05	Near top trending NE–SW	No
E0902234	Fig. 7d	6.41	Lower middle near massif	Same as V11946011
E1900290	Fig. 8f	4.81	Middle trending NW-SE	No
M0701211		3.05	Middle trending NW-SE	No
M1000254		4.57	Lower left	No
M1800778		3.05	Upper middle	No
M2200115		4.57	Top trending NE–SW	No
R0901059		3.21	Lower left	No
V05231008	Fig. 8c	19	Lower middle and bottom	No
V05543011	Fig. 8b	19	Upper middle	Maybe
V06367023	Fig. 8a	38	Middle trending E–W	No
V11634008	Fig. 7b	38	Top near boot-shaped massif	Same as V11946011
V11946011	Fig. 7b	38	Top near boot-shaped massif	Yes
		Remainder of Chryse Planitia/Arabia Terra		
E0301368		6.05	Near bottom trending N–S	No
E0400508		4.43	Middle; stacked lineations	Same as E1002709
E1002709	Fig. 12a	4.63	Middle; stacked lineations	Maybe
E1202808		1.54	Bottom; stacked lineations	Same as E1002709
E1203138		4.63	Upper middle	No
E2300131	Fig. 12e	6.34	Upper middle	No
FHA00678		1.56	Middle trending E–W	No
M0704326	Fig. 10	4.60	Middle; stacked ridges	Yes
M0807100		2.96	Bottom trending NW-SE	No
M0905927		3.07	Top trending E–W	No
M1700389	Fig. 12b	4.63	Lower mid; stacked lineations	Maybe
M2100888		4.61	Lower mid; stacked lineations	Maybe
R0400818		3.09	Middle; stacked lineations	Same as E1002709
R0900876		3.09	Middle; stacked lineations	Same as E1002709
R0902795		4.88	Throughout	No
R0902829	Fig. 12f	4.88	Top and middle	No
R0904036		6.47	Throughout	No
R1100209	Fig. 12c	4.84	Middle between massifs	No
R1303266		3.24	Middle	No
R1502318		4.83	Throughout	No
R1600661	Fig. 12d	1.63	Throughout	No
R1602478		3.11	Middle; stacked lineations	Same as E1002709
V09575018		19	Middle and bottom	Same as V11422004

(*continued on next page*)

Table A.1 (*continued*)

Image #	Shown in	Res. (m/pixel)	Location of feature(s) in image	Candidate coastal ridge?
V10486009	Fig. 9b	19	Top and upper middle	No
V11172003	Fig. 9c	19	Upper middle	No
V11422004	Fig. 9a	19	Throughout	No

Table A.2
Isidis Planitia Images with ridges not immediately dismissed as wrinkle or aeolian ridges

Image #	Shown in	Res. (m/pixel)	Location of feature(s) in image	Candidate coastal ridge?
		Parker et al. (1993) region		
E0101889	Fig. 15e	4.45	Upper mid. trending NE–SW	Same as V14139013
M1500469	Fig. 15f	2.95	Upper middle trending E–W	No
R0401310	Fig. 15d	6.23	Lower middle	No
V05652010		73	Top trending N-S	Same as V14139013
V11980007	Fig. 15a	18	Lower middle	No
V12604006	Fig. 15c	18	Bottom right	Yes
V14139013	Fig. 15b	18	Middle trending N–S	Yes
		Remainder of Isidis Planitia		
E0201040	Fig. 17f	4.49	Lower mid. trending NE–SW	No
E0202616		2.96	Top trending N–S	No
E0202618		2.98	Middle trending NE–SW	No
E0300958	Fig. 17b	5.83	Lower mid. north of massif	Maybe
E0501576		4.40	Top trending NE–SW	No
E0502100		2.91	Bottom trending NW–SE	No
E2301442	Fig. 17c	4.67	Bottom trending NE–SW	No
FHA00994	Fig. 17e	1.49	Bottom trending NW–SE	No
M0203053		2.91	Top to mid. trending N–S	No
M0900110		2.97	Bottom trending E–W	No
M0902298	Fig. 17d	5.92	Middle	No
R0400177	Fig. 17a	6.08	Top, north of crater	Maybe
R0900079		3.07	Middle trending E–W	No
V02431006	Fig. 16b	72	Lower middle	No

References

Adams, K.D., Wesnousky, S.G., 1998. Shoreline processes and the age of the Lake Lahontan highstand in the Jessup embayment, Nevada. Geol. Soc. Am. Bull. 110, 1318–1332.

Baker, V.R., 1978. The Spokane Flood controversy and the martian outflow channels. Science 202, 1249–1256.

Baker, V.R., 1979. Erosional processes in channelized water flows on Mars. J. Geophys. Res. 84, 7985–7993.

Baker, V.R., 1982. The Channels of Mars. University of Texas Press, Austin.

Baker, V.R., Milton, D.J., 1974. Erosion by catastrophic floods on Mars and Earth. Icarus 23, 27–41.

Baker, V.R., Strom, R.G., Gulick, V.C., Kargel, J.S., Komatsu, G., Kale, V.S., 1991. Ancient oceans, ice sheets and the hydrological cycle on Mars. Nature 352, 589–594.

Barnhart, C.J., Tulaczyk, S., Asphaug, E., Kraal, E.R., Moore, J., 2005. Ice-ridge pile up and the genesis of martian "shorelines." Lunar Planet. Sci. XXXVI. Abstract 1560.

Carr, M.H., 1981. Mars: A water-rich planet? Icarus 68, 187–216.

Carr, M.H., Head, J.W., 2003. Oceans on Mars: An assessment of the observational evidence and possible fate. J. Geophys. Res. 108, doi:10.1029/2002JE001963. 5042.

Christensen, P.R., Jakosky, B.M., Kieffer, H.H., Malin, M.C., McSween Jr., H.Y., Nealson, K., Mehall, G.L., Silverman, S.H., Ferry, S., Caplinger, M., Ravine, M., 2004. The Thermal Emission Imaging System (THEMIS) for the Mars 2001 Odyssey mission. Space Sci. Rev. 110, 85–130.

Clifford, S.M., Parker, T.J., 2001. The evolution of the martian hydrosphere: Implications for the fate of a primordial ocean and the current state of the northern plains. Icarus 154, 40–79.

Craddock, R.A., Maxwell, T.A., 1993. Geomorphic evolution of the martian highlands through ancient fluvial processes. J. Geophys. Res. 98, 3453–3468.

Frey, H., Jarosewich, M., 1982. Subkilometer martian volcanoes: Properties and possible terrestrial analogs. J. Geophys. Res. 87, 9867–9879.

Golombek, M.P., Bridges, N.T., 2000. Erosion rates on Mars and implications for climate change: Constraints from the Pathfinder landing site. J. Geophys. Res. 105, 1841–1853.

Golombek, M.P., Anderson, F.S., Zuber, M.T., 2001. Martian wrinkle ridge topography: Evidence for subsurface faults from MOLA. J. Geophys. Res. 106, 23811–23821.

Golombek, M.P., Grant, J.A., Crumpler, L.S., Greeley, R., Arvidson, R.E., and the Athena Science Team, 2005. Climate change from the Mars Exploration Rover landing sites: From wet in the Noachian to dry and desiccating since the Hesperian. Lunar Planet. Sci. XXXVI. Abstract 1539.

Grizzaffi, P., Schultz, P.H., 1989. Isidis basin: Site of ancient volatile-rich debris layer. Icarus 77, 358–381.

Guest, J.E., Butterworth, P.S., Greeley, R., 1977. Geological observations in the Cydonia region of Mars from Viking. J. Geophys. Res. 82, 4111–4120.

Head, J.W., Kreslavsky, M.A., Hiesinger, H., Ivanov, M.A., Pratt, S., Seibert, N., Smith, D.E., Zuber, M.T., 1998. Oceans in the past history of Mars: Test for their presence using Mars Orbiter Laser Altimeter (MOLA) data. Geophys. Res. Lett. 25, 4401–4404.

Head, J.W., Hiesinger, H., Ivanov, M.A., Kreslavsky, M.A., Pratt, S., Thomson, B.J., 1999. Possible ancient oceans on Mars: Evidence from Mars Orbiter Laser Altimeter data. Science 286, 2134–2137.

Head, J.W., Mustard, J.F., Kreslavsky, M.A., Milliken, R.E., Marchant, D.R., 2003. Recent ice ages on Mars. Nature 426, 797–802.

Head, J.W., Marchant, D.R., Agnew, M.C., Fassett, C.I., Kreslavsky, M.A., 2006. Extensive valley glacier deposits in the northern mid-latitudes of

Mars: Evidence for Late Amazonian obliquity-driven climate change. Earth Planet. Sci. Lett. 241, 663–671.

Kargel, J.S., Baker, V.R., Beget, J.E., Lockwood, J.F., Pewe, T.L., Shaw, J.S., Strom, R.G., 1995. Evidence of ancient continental glaciation in the martian northern plains. J. Geophys. Res. 100, 5351–5368.

King, C.A.M., 1972. Beaches and Coasts, second ed. Arnold, London.

Kraal, E.R., Asphaug, E., Moore, J.M., Lorenz, R.D., 2006. Quantitative geomorphic modeling of martian bedrock shorelines. J. Geophys. Res. 111, doi:10.1029/2005JE002567. E03001.

Kreslavsky, M.A., Head, J.W., 2002a. Fate of outflow channel effluents in the northern lowlands of Mars: The Vastitas Borealis formation as a sublimation residue from frozen ponded bodies of water. J. Geophys. Res. 105, doi:10.1029/2001JE001831. 5121.

Kreslavsky, M.A., Head, J.W., 2002b. Nature and evolution of young latitude-dependent water-ice-rich mantle. Geophys. Res. Lett. 29, doi:10.1029/2002GL015392.

Leverington, D.W., Ghent, R.R., 2004. Differential subsidence and rebound in response to changes in water loading on Mars: Possible effects on the geometry of ancient shorelines. J. Geophys. Res. 109, doi:10.1029/2003JE002141. E01005.

Lorenz, R.D., Kraal, E.R., Eddlemon, E.E., Cheney, J., Greeley, R., 2005. Sea-surface wave growth under extraterrestrial atmospheres: Preliminary wind tunnel experiments with application to Mars and Titan. Icarus 175, 556–560.

Lucchitta, B.K., Ferguson, H.M., Summers, C.A., 1986. Sedimentary deposits in the northern lowland plains, Mars. Proc. Lunar Sci. Conf. 17 (1). J. Geophys Res. 91 (Suppl.), E166–E174.

Malin, M.C., Edgett, K.S., 1999. Oceans or seas in the martian northern lowlands: High resolution imaging tests of proposed coastlines. Geophys. Res. Lett. 26, 3049–3052.

Malin, M.C., Edgett, K.S., 2001. Mars Global Surveyor Mars Orbiter Camera: Interplanetary cruise through primary mission. J. Geophys. Res. 106, 23429–23570.

Malin, M.C., Danielson, Ingersoll, A.P., Masursky, H., Veverka, J., Ravine, M.A., Soulanille, T.A., 1992. Mars Observer Camera. J. Geophys. Res. 97, 7699–7718.

McGill, G.E., 1986. The giant polygons of Utopia, northern martian plains. Geophys. Res. Lett. 26, 3049–3052.

Mifflin, M.D., Wheat, M.M., 1979. Pluvial lakes and estimated pluvial climates of Nevada. Nevada Bur. Mines Geol. Bull. 94, 1–57.

Milliken, R.E., Mustard, J.F., Goldsby, D.L., 2003. Viscous flow features on the surface of Mars: Observations from high-resolution Mars Orbiter Camera (MOC). J. Geophys. Res. 108 (E6), doi:10.1029/2002JE002005. 5057.

Morrison, R.B., 1964. Lake Lahontan: Geology of southern Carson Desert, Nevada. U.S. Geol. Surv. Prof. Paper 401.

Mustard, J.F., Cooper, C.D., Rifkin, M.K., 2001. Evidence for recent climate change on Mars from the identification of youthful near-surface ground ice. Nature 412, 411–414.

Parker, T.J., 1998. Mapping of possible "Oceanus Borealis" shorelines on Mars: A status report. Lunar Planet. Sci. XXIX. Abstract 1965.

Parker, T.J., Currey, D.R., 2001. Extraterrestrial coastal geomorphology. Geomorphology 37, 303–328.

Parker, T.J., Saunders, R.S., Schneeberger, D.M., 1989. Transitional morphology in west Deuteronilus Mensae, Mars: Implications for modification of the lowland/upland boundary. Icarus 82, 111–145.

Parker, T.J., Gorsline, D.S., Saunders, R.S., Pieri, D.C., Schneeberger, D.M., 1993. Coastal geomorphology of the martian northern plains. J. Geophys. Res. 98, 11061–11078.

Scott, D.H., Chapman, M.G., Rice, J.W., Dohm, J.M., 1991. New evidence of lacustrine basins on Mars: Amazonis and Utopia Planitia. Proc. Lunar Sci. Conf. XXI, 189–198.

Scott, D.H., Dohm, J.M., Rice, J.W., 1995. Map of Mars showing channels and possible paleolakes. U.S. Geol. Surv. Misc. Inv. Series Map I-2461.

Smith, D.H., Zuber, M.T., Frey, H.V., Garvin, J.B., Head, J.W., Muhleman, D.O., Pettengill, G.H., Phillips, R.J., Solomon, S.C., Zwally, H.J., Banerdt, W.B., Duxbury, T.C., 1998. Topography of the Northern Hemisphere of Mars from the Mars Orbiter Laser Altimeter. Science 279, 1686–1692.

Squyres, S.W., 1978. Martian fretted terrain: Flow of erosional debris. Icarus 34, 600–613.

Squyres, S.W., 1979. The distribution of lobate debris aprons and similar flows on Mars. J. Geophys. Res. 84, 8087–8096.

Squyres, S.W., Carr, M.H., 1986. Geomorphic evidence for the distribution of ground ice on Mars. Science 231, 249–252.

Theilig, E., Greeley, R., 1979. Plains and channels in the Lunae Planum–Chryse Planitia region of Mars. J. Geophys. Res. 84, 7994–8010.

Watters, T.R., 2004. Elastic dislocation modeling of wrinkle ridges on Mars. Icarus 171, 284–294.

Webb, V.E., 2004. Putative shorelines in northern Arabia Terra, Mars. J. Geophys. Res. 109, doi:10.1029/2003JE002205. E09010.

Wilson, S.A., Zimbelman, J.R., 2004. Latitude-dependent nature and physical characteristics of transverse aeolian ridges on Mars. J. Geophys. Res. 109, doi:10.1029/2004JE002247. E10003.

Zimbelman, J.R., Irwin, R.P., 2005. Field investigation of shoreline barrier ridges from glacial lakes in Nevada, as analogs for potential pluvial landforms on Mars. Geol. Soc. Am. Abs. Prog. 37 (7), 513.

Zimbelman, J.R., Johnston, A.K., 2001. Improved topography of the Carrizozo lava flow: Implications for emplacement conditions. In: Crumpler, L.S., Lucas, S.G. (Eds.), Volcanology in New Mexico. New Mexico Museum of Natural History and Science, Albuquerque, NM. Bull. 18, pp. 131–136.

Zimbelman, J.R., Williams, S.H., Irwin, R.P., Rivera, E.J., Graves, L., Ghatan, G., 2005. Shorelines in the western United States as analogs for hypothesized shoreline features on Mars. Lunar Planet. Sci. XXXVI. Abstract 1733.

Zuber, M.T., Smith, D.E., Solomon, S.C., Muhleman, D.O., Head, J.W., Garvin, J.B., Abshire, J.B., Bufton, J.L., 1992. The Mars Observer Laser Altimeter investigation. J. Geophys. Res. 97, 7781–7797.